AD-A039 700 GEORGIA INST OF TECH ATLANTA ENGINEERING EXPERIMENT --ETC F/G 9/1
HANDBOOK FOR ELECTROMAGNETIC COMPATIBILITY DESIGN OF ELECTRONIC--ETC(U)
JUN 75 J A WOODY, A R HOWLAND, J C TOLER DOT-FA74WA-3372

UNCLASSIFIED FAA-RD-76-71 NL

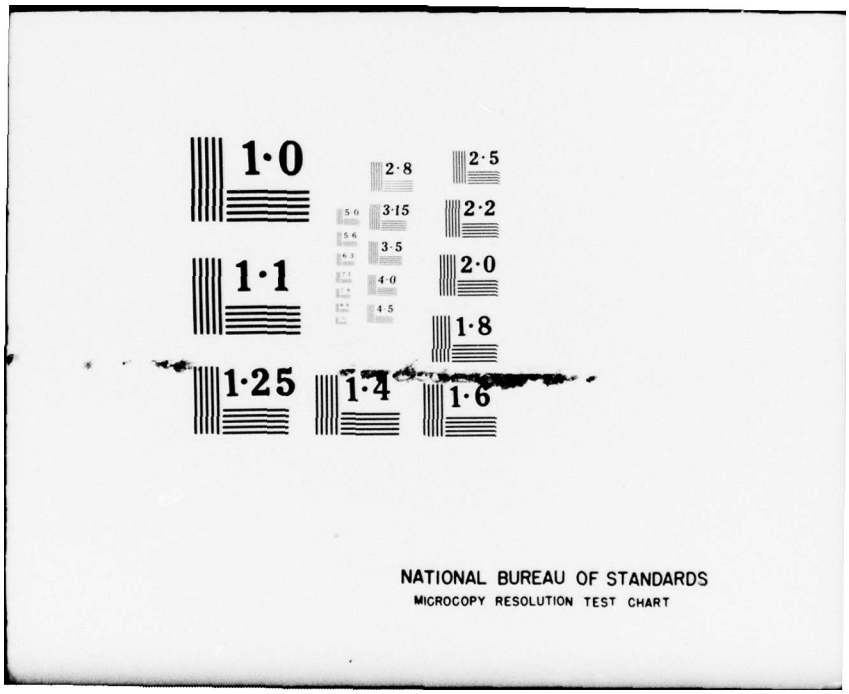
| OF |
AD
A039700





END

DATE
FILMED
6-77


1·0
1·1
1·25
1·4
1·6
1·8
2·0
2·2
2·5
2·8
3·15
3·5
4·0
4·5
5·0
5·6
NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

REPORT NO. FAA-RD-76-71

HANDBOOK FOR ELECTROMAGNETIC COMPATIBILITY DESIGN OF ELECTRONIC EQUIPMENTS

J. A. WOODY
A. R. HOWLAND
J. C. TOLER

AD A039700

AD No.
DDC FILE COPY

JUNE 1975

DDC
RECEIVED
MAY 1977
B

Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FAA-RD-76-71		

4. Title and Subtitle	5. Report Date
Handbook for Electromagnetic Compatibility Design of Electronic Equipments.	June 1975
	6. Performing Organization Code
	8. Performing Organization Report No.
7. Author(s) J. A. Woody, A. R. Howland, and J. C. Toler	
9. Performing Organization Name and Address Engineering Experiment Station Georgia Institute of Technology Atlanta, Georgia 30332	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DOT-FA74WA-3372
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Washington, DC 20591	13. Type of Report and Period Covered Research
	14. Sponsoring Agency Code ARD-350

15. Supplementary Notes

79 p.

16. Abstract

This Handbook presents equipment level guidelines for use by personnel who must comply with test requirements in contractually imposed electromagnetic compatibility standards. The Handbook is a key element in an overall Federal Aviation Administration electromagnetic compatibility program based on an a priori design emphasis complimented by an a posteriori test emphasis. Design guidelines are presented for functional units, i.e., power suppliers, amplifiers, mixers, local oscillators, control circuit, etc. that make up analog and digital electronic equipments. For each functional unit, broad overall concepts are first presented followed by specific guidelines tailored to aid the designer. References which support and supplement the design information are identified throughout the Handbook.

17. Key Words	18. Distribution Statement
Design Guidelines, Electromagnetic Compatibility, Electronic Equipments	Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	80	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

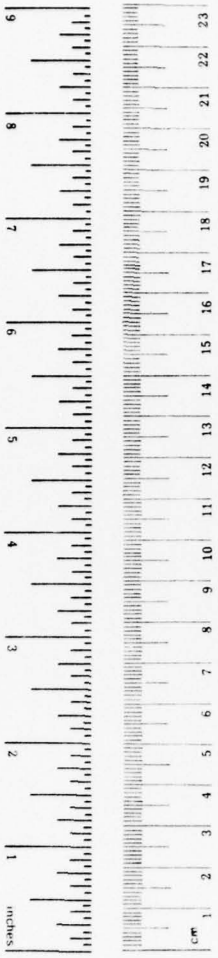
153850 A

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

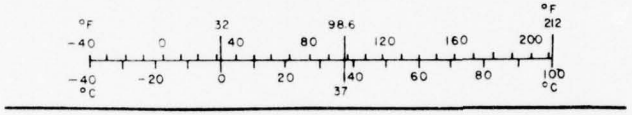
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

This Handbook was prepared in the Georgia Tech Engineering Experiment Station and fulfills the Task I requirements under Contract No. DOT-FA74WA-3372. Preparation of the Handbook was under the general supervision of Mr. D. W. Robertson, Director of the Electronics Technology Laboratory, and Mr. J. C. Toler was the Project Director. The Handbook provides design guidelines for use by Federal Aviation Administration personnel as well as contractor personnel who must comply with equipment level electromagnetic compatibility standards.

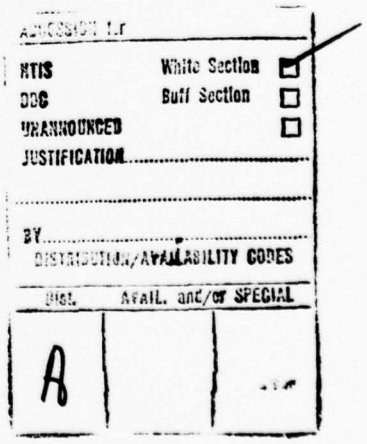


TABLE OF CONTENTS

		PAGE
I.	INTRODUCTION	1
	1.1 Purpose	1
	1.2 Broad Overview	2
	1.3 Electromagnetic Environment	3
	1.4 Handbook Format	4
II.	COMPONENT SELECTION	5
	2.1 Broad Guidelines	5
	2.2 Specific Guidelines	6
III.	ELECTRONIC DESIGN	8
	3.1 Broad Guidelines	8
	3.2 Power Supplies	9
	3.3 Control Units	12
	3.4 Amplifiers	14
	3.5 Display Units	15
	3.6 Transmitters	17
	3.7 Receivers	22
	3.7.1 Preselector	24
	3.7.2 Mixer	26
	3.7.3 Local Oscillator	27
	3.7.4 IF Amplifier	28
	3.7.5 Design Guidelines	29
	3.8 Digital Units	31
	3.9 Electromechanical Units	33
IV.	MECHANICAL DESIGN	34
	4.1 Broad Guidelines	34
	4.2 Functional Subunit Layout	34
	4.3 Compartmentalization	36
	4.4 Chassis and Enclosures	37
	4.4.1 Structural Materials	38
	4.4.2 Seams	39
	4.4.3 Penetrations and Apertures	43
	4.4.4 Bonding	51

TABLE OF CONTENTS (continued)

PAGE

4.5 Cabling 56
4.5.1 Cable Selection 57
4.5.2 Cable Shield Grounding 58
4.5.3 Connector Selection and Installation 59
4.5.4 Cable Routing. 60
4.6 Grounding 61
V. LIGHTNING STROKES. 64
VI. NUCLEAR ELECTROMAGNETIC PULSE PHENOMENA. 67
VII. REFERENCES 70

LIST OF FIGURES

PAGE

1. Block Diagram of a Transmitter. 19
2. Block Diagram of a Superheterodyne Receiver 23
3. Shielding Effectiveness of Seams as a Function of Screw Spacing . 40
4. Shielding Effectiveness of Seams With a Gasket as a Function of Pressure. 42
5. Reduction of Shielding Effectiveness of Typical Enclosure With Unfiltered Wire Through Shield Opening. 44
6. Reduction of Shielding Effectiveness of Typical Enclosure with Unfiltered Wire Through a Connector Pin 45
7. Use of Circular Type Waveguide for Installation of Controls . . . 47
8. Shielding for Recessed Shafts 48
9. Pressure Drop Versus Air Flow for Various Materials 50
10. Method of Mounting Wire Screen Over a Large Aperture. 52
11. Acceptable Methods of Shielding Panel-Mounted Meters. 53
12. Shielding Effectiveness of Conductive Glass to High Impedance Waves 54
13. Shielding Effectiveness of Conductive Glass to Plane Wave Propagation. 54
14. Shielding Effectiveness of Ten Ohm Conductive Glass 55
15. A Suggested Method for Attaching the Bonding or Halo at a Connector. 60

I. INTRODUCTION

1.1 Purpose

This Handbook provides information that will enable design engineers to more readily achieve electromagnetic compatibility objectives established for electronic equipments used by the Federal Aviation Administration (FAA). The motivation for the Handbook lies in the fact that, when equipment electromagnetic compatibility is realized, air traffic safety and scheduling will be favorably influenced. The specific guidelines presented herein have been developed with a thorough knowledge of the equipment types used by the FAA and information concerning the electromagnetic environment within which these equipments must function. These guidelines, therefore, represent systematic design considerations necessary in assuring electromagnetic compatibility for FAA equipments.

This Handbook is a key element in an overall electromagnetic compatibility program based on a strong a priori emphasis during equipment design. This emphasis is coupled to an equally strong a posteriori emphasis on equipment test and evaluation. Consequently, this Handbook and the FAA Electromagnetic Compatibility Standards (FAA Reports No. FAA-RD-76-69, Appendices A and B and FAA-RD-76-70, Appendices A and B) for equipments are to be used as complimentary documents of equal importance.

From an operational viewpoint, FAA equipments include those used for communications, navigation, automated signal processing, electromechanical functions, and radar surveillance. Each of these operational equipments is composed of a combination of functional units such as power supplies, control circuits, amplifiers, mixers, oscillators, display circuits, electromechanical components, etc. In order to satisfy operational requirements, electromagnetic compatibility considerations must be designed into the functional units comprising FAA equipments. Preparation of this Handbook has followed this concept by presenting pertinent design guidelines for equipment functional units. These guidelines initially present broad electromagnetic compatibility design considerations, if applicable. Then detailed design guidelines tailored to the specific functional unit are presented. Throughout the Handbook, references containing supporting and/or supplemental information are identified. Consequently, the more

important design considerations for equipment functional units are presented in the technical portions of the Handbook. However, if more detailed information regarding particular design considerations is desired, the references may then be used to advantage.

1.2 Broad Overview

Equipment level electromagnetic compatibility is achieved when performance degradations caused by either air coupled or wire coupled electromagnetic energy are reduced to tolerable limits. As such, equipment level electromagnetic compatibility requires that, in addition to incorporating those engineering practices and procedures that achieve the intended performance objective, there must also be close scrutiny of all electromagnetic interfaces. To illustrate this, equipment design can be viewed in terms of performance based on electromagnetic energy sources, sinks, and coupling paths. Traditional equipment design is a matter of coupling intended energy sources along desired paths to intended energy sinks. Electromagnetic compatibility equipment design is concerned with either intended or unintended energy sources that are coupled along intended or unintended paths to intended or unintended energy sinks. From this, it is obvious that the most effective approach to electromagnetically compatible equipment design is to either eliminate or reduce to tolerable levels the undesired sources of energy. When this approach is not feasible, the design emphasis must shift to include concern with coupling paths that minimize adverse electromagnetic interactions and to sinks for undesired energy that are as close as possible to the sources. This emphasis often involves the use of various shielding, filtering, grounding, and bonding techniques. It should be noted, however, that where these techniques result in energy reflection rather than absorption, the undesired energy is still present and a potential source of incompatibility.

In terms of a broad overview, equipment design for electromagnetic compatibility can be summarized as basically a matter of attention to undesired energy sources, sinks and coupling paths. The sources may be internal to the equipment or the electromagnetic environment within which the equipment must function. The sinks are undesired devices that absorb and dissipate the undesired energy. The coupling paths for the undesired energy are

extremely important because they often offer a means of energy decoupling via physical and/or electrical isolation.

1.3 Electromagnetic Environment

Although efforts have been made to tailor design guidelines in this Handbook to electromagnetic environments in FAA facilities [1], it must be recognized that these environments are highly variable from one location to another and are undefined in many locations. To assume that absolutely worst case environments will exist at every facility location results in unduly restrictive and cost ineffective design guidelines for FAA equipments. Consequently, this Handbook recognizes that, at each facility, there is a reasonably constant and broadband ambient electromagnetic environment within which equipments must function reliably. The amplitude of this "background" environment is below that of many of the discrete signals of which it is comprised; hence, it is less severe than a worst case environment. Contributions to this environment are electrical/electronic devices within and external to the facility as well as non-manmade atmospheric noise signals. Superimposed on this ambient environment are numerous narrowband or discrete frequency signals and, in some cases, certain sources of high level broadband energy. The narrowband signals typically originate in electronic equipments such as transmitters used for communications and radar purposes; therefore, these environmental contributions may be continuous wave, interrupted continuous wave, pulse modulated, frequency modulated, amplitude modulated, etc. Conversely, the high level broadband energy is typically contributed by non-electronic devices such as arc welders, ignition systems, electric motors, etc. Therefore, an equipment designer concerned with electromagnetic compatibility must not only consider the broadband ambient electromagnetic environment, but also other broadband and narrowband energy sources which may be superimposed onto the ambient environment. In most instances, the equipment designer will have little or no control over any of these contributors to operational environments; however, to the extent possible he must be aware of these environments. For example, in designing a receiver, questions regarding co-channel and adjacent channel environments as well as out-of-band

signals that might be present at the antenna terminals must be a part of the designer's concern.

In addition to concerns regarding the influence of operational environments on equipment functioning, it is also imperative that designers be equally concerned that their designs do not contribute unnecessarily to an already congested national resource - the electromagnetic spectrum.

1.4 Handbook Format

Contents of this Handbook have been arranged under five major sections, each with appropriate subheadings. This section (Section I) is introductory, while Section II provides design guidelines for the selection of electromagnetically suitable components. For use after such components have been selected, electronic design considerations are provided as guidelines in Section III. In the next section, guidelines for the mechanical design of equipments are presented. The final section documents the references used throughout the Handbook.

Guidelines presented in the following sections cannot be viewed as step-by-step procedures for complying with electromagnetic compatibility standards. Rather, they are intended to direct the attention of designers concerned with component selection, electronic circuits, and mechanical features of equipments to electromagnetic compatibility principles that enhance reliable operation. Special emphasis is placed on electronic design guidelines for transmitters and receivers because (1) they are used extensively at essentially every type of FAA facility and (2) most interference problems reported at FAA facilities involved either transmitters, receivers, or both.

II. COMPONENT SELECTION

2.1 Broad Guidelines

Resistors, capacitors, inductors, integrated circuits, transformers, etc. are the basic components from which electronic circuits in functional units of FAA equipments are constructed. In most instances, the extent to which these components exhibit satisfactory electromagnetic characteristics will determine the extent to which functional units, and ultimately FAA equipments, are electromagnetically compatible. Consequently, it is not only logical but essential that careful before-the-fact attention be devoted to the selection of electromagnetically acceptable components. This attention should be as comprehensive as that devoted to other environmental requirements, i.e., vibration, shock, temperature, humidity, etc.

Broad design guidelines of importance in the selection of electromagnetically suitable components include (1) consideration of out-of-band performance characteristics and (2) circuit installation practices. In most cases, performance characteristics of components are available directly from the manufacturer only for a rather narrow range of operational conditions. As important as these characteristics are, it is of equal importance from an electromagnetic compatibility point-of-view to know performance characteristics under all operational conditions within which components must function. For example, knowledge of the response characteristics of components at the fundamental frequency is mandatory; however, whether electromagnetic compatibility is realized or not is often determined by component response characteristics at frequencies far removed from the fundamental. In many instances, circuit installation practices determine the significance of these out-of-band response characteristics. For example, component lead lengths can be such that resonance conditions at undesired frequencies are permitted. Also, installation procedures will often dictate the extent of mutual coupling between components in different circuits within a functional unit [2] [3].

2.2 Specific Guidelines

In general, the initial selection of components for design consideration will be made from the FAA document FAA-G-2100, Electronic Equipment, General Requirements. The following guidelines supplement this initial selection and provide specific electromagnetic aids to be followed in component selection:

- Since feed-through capacitors exhibit less lead inductance and thus provide more effective filtering at higher frequencies, they should be used in preference to lead-type capacitors where practical [4].
- When lead-type capacitors must be used, consider the lead inductance and its effect upon filtering effectiveness.
- Use only properly rated electrolytic capacitors where high ripple or transient voltages are present [5].
- For electrolytic capacitors, choose a type which exhibits a low RF impedance.
- Use resistors which have the lowest stray inductance and capacitance characteristics.
- Select RF circuit components that operate compatibly over frequency ranges extending well above the circuit operating frequency.
- In circuits where stray coupling may be detrimental, consider the use of shielded inductors.
- Because of stray capacity associated with large inductances, consider the use of several small inductors in additional filter sections instead of a single section filter for providing high insertion loss at low frequencies.
- Observe the saturation characteristics of ferrite core materials because high level pulses may lower the inducatance and reduce the insertion loss.

- Wherever possible, use shielded relays and ground the shield.
- Use RC network filters for arc and transient RF energy suppression across electromechanical switches, relays, and commutator power circuit contacts.
- The input transformers for isolation amplifiers should have effectively shielded primary windings.
- Power transformers for susceptible circuits should have electrostatic shields between the primary and secondary windings. The shields and the transformer case should be grounded to the equipment chassis.
- Use shielded hookup wire for signal conductors inside equipments where it is necessary to prevent interference coupling between internal conductors.
- Select connector types which will provide a sufficient number of pins for individual shield terminations.
- Select connectors that are able to withstand environmental conditions without degradation of the shielding characteristics of the connector.
- The connector shell at the interface of the two connector halves must make positive contact before the two power contacts mate and must maintain contact until after the power contacts break.

III. ELECTRONIC DESIGN

3.1 Broad Guidelines

Electronic design guidelines as contrasted to mechanical design guidelines are directed primarily toward circuit design considerations and are presented for equipment functional units such as power supplies, control units, amplifiers, display units, transmitters, receivers, digital units, and electromechanical units. Each of these is characterized by the fact that they receive an input signal, act on this signal, and then couple the resultant signal from the unit at the output.

In the receiver example mentioned in the Introduction, it was noted that electronic designers must consider the electromagnetic environment and the possibility of undesired signals at the input terminals of the receiver. In addition, an indepth emphasis must also be given to the reception of undesired signals by paths other than the input terminals. This broad guideline requires a continual awareness of many design features, but shielding and filtering are of particular concern. Shielding guidelines are considered to be primarily a non-circuit design consideration and are, therefore, presented in Section IV. Filtering guidelines are discussed throughout this section; however, the discussion is most often in terms of guidelines to provide high frequency bypassing, to prevent specific signals from reaching some component or circuit, to decouple units from each other, etc. Regardless, though, of where and how shielding and filtering guidelines are presented, the basic concern is the fact that undesired signals may enter equipments both at input terminals and at numerous other points. As a broad design guideline, this should be minimized by appropriate electronic and mechanical design techniques.

Another important and often neglected broad guideline is that undesired signals in equipments must be dealt with beginning at the initial point of entry. These signals may develop relatively significant voltages across high impedance components in a circuit. If this component is followed by a device that amplifies the undesired signal, all of the ingredients for electromagnetic incompatibility exist. Thus, basic decisions to be made at the beginning of equipment design are (1) how undesired signal entries are

to be dealt with and (2) what should be the impedance levels in the units. It is recognized that there may not be a choice in these impedance levels. For example, if components must operate in conjunction with each other at some characteristic impedance, then there is little or no choice about the operating impedance level. As a broad design guideline for situations in which high impedance levels are necessary, thorough by-passing of the high impedance circuit components for out-of-band signals should be provided.

Continual awareness that undesired signals are entering equipments via the intended input terminals as well as many other paths, recognition of the fact that these undesired signals are best dealt with at their entry point, and before-the-fact selection of impedance levels represent broad design guidelines that will enhance the electromagnetic compatibility of electronic equipments. In the following paragraphs, specific guidelines applicable to functional units comprising FAA equipments are presented.

3.2 Power Supplies

Power supplies are basic functional units in essentially all FAA equipments. Their purpose is to convert the locally available power to a form that can be used by signal processing circuitry within equipments. From an electromagnetic compatibility point-of-view, power supplies are of concern primarily because of their extensive interconnections with other functional units within equipments [6]. Because of these interconnections, undesired signals generated within a power supply may be readily coupled to other functional units. Further, in cases where several functional units are connected to the same power supply, undesired signals generated in one unit may be coupled through the power supply to the other units. Therefore, the importance of an emphasis on electromagnetically compatible design for power supplies is evident.

Undesired signals are generated in power supplies by nonlinear circuit elements and by rapidly changing load demands. Diodes, SCR's, and rectifiers are excellent sources of wideband undesired signals [7]. These circuit components are fundamental to functional unit design and the undesired signals generated by them are usually controlled by shielding and filtering [8]. Inverters and power supplies which contain SCR's typically require more shielding than other types of power supplies.

FAA equipments often use regulated power supplies comprised of a raw supply followed by an active regulator. The regulator can function properly only if an input adequate to supply the load is received. Thus, the size of the raw power supply is determined on the basis of the worst combination of the available input power and output load demand. The response time of the control loop used in the regulator is also important [9]. If this loop is sufficiently broadband and the raw supply is sized properly, then the effects caused by rapidly changing load demands will be significantly reduced; otherwise, the power supply will operate as though it generated undesired signals.

Undesired interactions resulting from common power supply connections can be effectively eliminated by careful consideration of circuit layout and cabling [6] along with specific attention to decoupling and isolation techniques as equipments are designed and developed. The use of individual power supplies to feed separate functional units is one compatibility technique to be considered.

Power supply terminals on a functional unit are indeed input terminals, and it is important to recognize that they may also be signal input terminals. Input filters must often be used both to prevent undesired signal coupling and to provide decoupling between circuit stages [9]. From a compatibility viewpoint, the designer must assure that sufficient decoupling has been provided so that pickup of stray signals will neither lead to the production of even stronger stray signals nor cause unit instability or oscillation.

Specific guidelines for the electromagnetic design of power supplies are as follows:

- If the use of separate power supplies is not technically or economically possible, use well regulated supplies to reduce common impedance coupling between circuits.
- Ensure that all circuits using a common power supply are compatible with each other.
- Locate all circuits using a common power supply as close together as practicable.

- Employ power line filters on the ac or dc mains to prevent external interference from entering the equipment via the power supply and to prevent power supply switching transients or other signals generated internal to the equipment from being introduced onto the primary power leads.
- Use the minimum capacitance necessary in the power supply output filter for adequate fundamental frequency filtering.
- Effectively separate input and output wiring of the power supply.
- Provide effective electric and magnetic field shielding of the power supply.
- Select rectifier diodes that will operate at the lowest current density in proporation to the manufacturer's maximum current rating.
- Select rectifier diodes with working and peak inverse voltage ratings that will not be exceeded.
- Use the lowest possible diode switching rates.
- Allow for diode-to-diode variations in operating characteristics of at least 2 to 1.
- To maintain a low power supply impedance for all circuit functions, output capacitors should exhibit a low impedance well into the RF range.
- Insure that the response time of the power supply regulator is fast enough to handle short duration transitory loading effects and to suppress high frequency power supply ripple.
- Provide an adequate RF bypass for zener reference diodes.
- Adequately shield and carefully isolate high voltage power supplies from sensitive circuits.

3.3 Control Units

The facility arrangement at many FAA installations is such that operators use and control widely separated equipments. This arrangement provides an almost infinite number of coupling opportunities for undesired signals. The control units of primary concern are those used by an operator to evoke a response in an equipment. They vary in size and complexity from simple push-to-talk switches to remotely located consoles that direct the functioning of automated systems. They may be coupled together via inter-unit cables, land lines, VHF or UHF radiated signals or microwave point-to-point communications systems.

Careful attention to the energy sink, source, and coupling path concept is necessary if compatibility goals for control units are to be achieved. From an electromagnetic point-of-view, transmission and reception of signals is the primary concern in control unit design. Line driver subunits within the control unit must be designed to direct all undesired signals generated in the control unit to an appropriate energy sink. Similarly, line receiver subunits must be designed to respond to the desired signal only and to couple all undesired signals picked up enroute from the sending source to an appropriate energy sink. For control units interconnected by cables, the cables must be prevented from functioning as transmitting or receiving antennas by properly isolating them from the sources of undesired signals.

Compatible control unit design also requires that there be a thorough awareness of the equipment grounding system at the FAA facility where the equipment is to be used. With this knowledge, the designer will be able to incorporate grounding and shielding procedures that avoid completing ground loops and pickup of undesired signals.

The predominate sources of undesired signals within control units are components which abruptly interrupt the control signal path, such as switches, relays, SCR's, switching transistors, etc. [10] [11]. Such components will produce transients when operated in conjunction with an inductive component unless proper suppression techniques are used [12]. The following guidelines will aid in reducing such transients and their effects:

- To minimize arcing, retard voltage buildup across switch gaps during contact separation.
- To minimize sharp wave-front transients, limit the surge of current through switches during openings or closings.
- Some reduction of interference may be accomplished by placing a resistance across either the load (if reactive) or the switching component. Further reduction, if necessary, may be achieved by using RC networks and/or diodes [13].
- When diodes are used across switches and relays in control units, the current rating of the diodes should be equal to or greater than the load currents.
- Place suppression devices as close as possible to sources of transients.
- Peak inverse voltage ratings of silicon and germanium diodes should exceed the supply voltage by at least 120 percent.
- Use back-to-back diodes in ac circuits. The peak inverse voltage must exceed the supply voltage.
- When varistors are used in control units, the characteristic curve resistance knee must be above the supply voltage, and the heat dissipating area must be designed sufficiently large.
- Wherever possible, use diode or transistor switches instead of electromechanical contact closures.
- Reduce relay bounce and chatter in control units by using mechanically damped devices and by perhaps shock mounting the relay.
- Wherever possible, use shielded relays and electrically ground the shield.
- For severe cases, provide additional filtering on the operational and functional leads of the relay or switch.
- When control unit switching speed is not critical, the basic approach in designing interference reduction for SCR circuitry should be to

localize and contain the initial high rate-of-rise of current to as small a section of the circuit as possible.

- Operate parallel and potentially interacting SCR circuits from low reactance supply lines.
- If the supply line to the control unit is highly reactive, consider using separate transformers to feed parallel SCR branch circuits.
- Keep both leads of power circuit wiring routed together in control units; avoid loops that encircle sensitive control circuitry.
- Consider the use of time-delayed sequential switching of control signals to avoid inducing undesired signals into sensitive circuitry.
- Consider the ordering of control switching to permit high level transitory circuits to energize before low level circuits are energized.

3.4 Amplifiers

Amplifiers are necessary functional units in FAA equipments and are normally tailored by the designer to support specific equipment performance goals. Consequently, amplifiers whose operation has been optimized for such purposes as high gain, linearity, frequency response, etc. are in common use. Circuits used in these amplifiers vary widely and are usually of a multistage design. The amplifier may be either narrowband or broadband with either balanced or unbalanced inputs. Because of their wide utilization as well as their ability to influence undesired signal generation and coupling, amplifiers must receive careful electromagnetic compatibility design attention. Amplifiers are often functional subunits within an equipment. The signal processing circuitry in a receiver or transmitter contains many amplifiers. On the other hand, a line amplifier is an example of a functional unit "amplifier" that is used in many FAA installations. The considerations which lead to electromagnetically compatible amplifiers are the same for subunits and functional units. Additional considerations for transmitter power amplifiers and receiver IF amplifiers are presented in Sections 3.6 and 3.7, respectively.

Equipment performance requirements generally dictate the number and type of amplifiers necessary for a particular purpose. Regardless of the system performance requirements, the amplifier layout should be designed such that low level signals are conducted over the shortest possible distance. This may be accomplished by locating the amplifier close to the detector output or source of signal. The out-of-band performance of amplifiers must be controlled to assure that parasitic oscillations do not exist. It is also desirable to decouple between the individual stages of multistage amplifiers and to fix the operating point of active elements by circuit design rather than rely on component characteristics that may vary with temperature. Other design considerations include assuring that (1) use of a marginal number of amplifier stages, each with inadequate inter-stage decoupling and out-of-band bypassing, is not permitted, (2) the electronic grounding philosophy established for the equipment and facility is closely adhered to, and (3) the response function of input connections used for power supply connection, gain control, and switched feedback network connection is limited to that necessary for the desired signal.

The following specific guidelines will provide assistance in satisfying electromagnetic compatibility requirements for amplifiers:

- In the design of all low level amplifier circuits, always consider the effects of common mode voltages, ground loops, and stray coupling of local ambient signals [14] [15] [16].
- Decouple all amplifier input connections.
- Signal inputs to functional unit "amplifiers" operating below 1 MHz should be balanced [17].
- Input transformers for isolation amplifiers should have effectively shielded primary windings.

3.5 Display Units

FAA display units consist primarily of either electrostatically or magnetically controlled cathode-ray tubes (CRT) and their associated driver circuits. The function of the CRT is to display information in an

easily read manner which implies that there is necessarily a large aperture in the equipment enclosure. This necessitates the shielding of subunits within the display unit as if there were no equipment enclosure unless, of course, the aperture can be shielded as described in Section 4.4.3. CRT's by their very nature are extremely susceptible to magnetic fields and are, therefore, routinely enclosed, except for their faces, in a magnetic shield. The amount of shielding required [18] is primarily a function of the strength of the magnetic field generated by adjacent circuit components such as power transformers. Adjacent CRT's may also create interference if improperly shielded.

The driver circuits for the CRT's are composed of sweep generators and amplifiers with their corresponding power supplies. The sweep generators are usually "sawtooth" oscillators and as such are capable of generating undesired broadband signals. The amplifiers on the other hand are generally designed to provide high gain for low level signals and, hence, can act as sensitive receivers. For these reasons, significant attention must be directed to the reduction of undesirable coupling between display subunits as well as between the display unit and other functional units.

The following guidelines are provided to aid in the design of display units:

- Segregate power, video, pulse, and deflection leads. If possible, make the crossover of such leads at right angles.
- Filter all power supply leads to the sweep generators at the point where they enter the shield surrounding the sweep circuit.
- Shield the cathode ray tube and its deflection yokes with a magnetic, high permeability material to prevent deflection fields from coupling to nearby susceptible circuits and to prevent external fields from deflecting the electron beam.
- Fit the magnetic shield as close as possible around the CRT.
- Consider the use of concentric magnetic shields separated by air or copper [19].

- Exercise caution in the placement of the focus coils to prevent electromagnetic interaction with the deflection yoke and other adjacent circuits. Remember that permanent magnet focus units have higher leakage fields than electromagnetic focus units and, hence, cause more interactions [20].
- Keep in mind that oscillations and, hence, picture distortion and coupling to adjacent circuits, can occur at the end of the trace if the magnetic field stored in the deflection yoke is not dissipated.
- Employ resistance damping, diode damping, secondary emission damping, or power feedback to dissipate magnetic fields stored in the deflection yoke at the end of each trace [21].
- Place components of pulse and sweep circuits as near as possible to their associated tubes and use point-to-point wiring.
- Assure that all indicator waveforms contain no unnecessary spikes and that the voltage levels of all pulses are no larger than necessary.
- Provide adequate shields around horizontal and vertical sweep generators. Particular attention should be given to the shielding of the horizontal sweep generator because its signal has a short period and, hence, will produce interference over a wide frequency range.
- Use coaxial cables for the input and output signal pulses of sweep generators. Also, use coaxial cables for video signals.
- Locate the sweep generators as close as possible to the cathode ray tube in order to keep the length of the pulse carrying leads to a minimum.

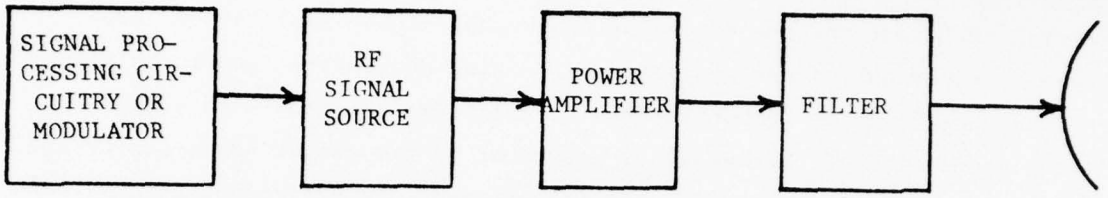
3.6 Transmitters

Transmitters are integral functional units of FAA's radar, communication, and navigational aid systems, and as such they are required

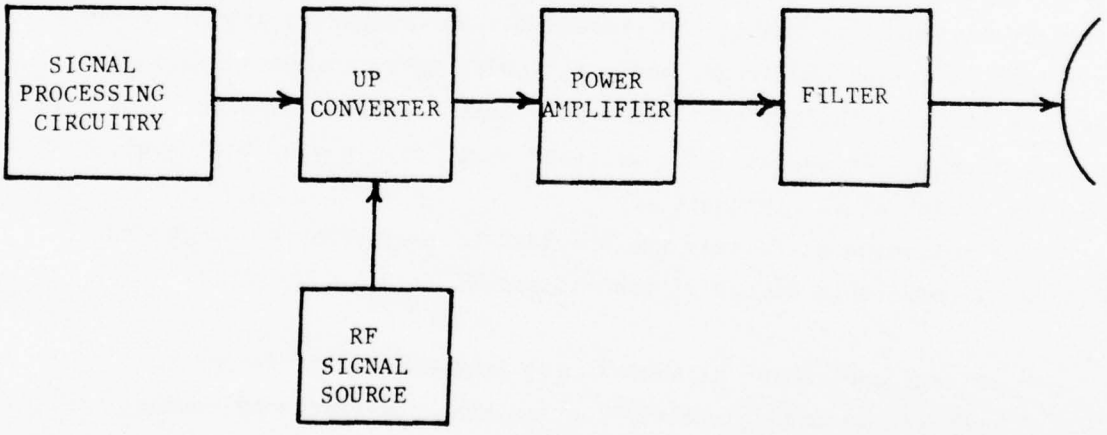
in large numbers at most FAA facilities. All transmitters operate in basically the same manner in that they accept a baseband signal and convert it to a high-level, modulated RF signal. A block diagram of a typical FAA transmitter is shown in Figure 1. The electromagnetic compatibility aspects of the oscillator, modulator (or upconverter), power amplifier, and output filter circuits of the transmitter are considered in the following paragraphs. Signal processing circuits (amplifiers interconnected in a variety of ways), power supplies, and control units which are also a part of the total transmitter are discussed in their respective sections of this Handbook.

The desired output signal from a transmitter is comprised of a carrier frequency signal and the necessary information-carrying modulation sidebands [22]. In addition to this desired output, undesired out-of-band signals may also be radiated as unnecessary modulation sidebands, as harmonics of the carrier, and as signals not directly related to the carrier. These undesired signals result from the many nonlinearities required in the transmitter design and the broadband noise produced by the final power amplifier. Some of the undesired signals can be reduced or eliminated by good circuit design practices [24]; however, others are inherent to the transmitter design and, therefore, their effects must be minimized by control techniques other than circuit design, e.g., filtering and shielding. In either case, control of these undesired output signals is paramount in achieving electromagnetic compatibility for transmitters.

Effective control of transmitter spurious output signals normally requires the use of several interference reduction techniques. The most effective technique is obviously to design circuits, if possible, that do not generate undesired signals. Thus, selection of components which are inherently linear or as near to being linear as practicable is required. Also, to the extent possible the frequency source should be designed to produce only one frequency. For example, if a crystal oscillator followed by a multiplier chain is used to generate the carrier frequency signal, then high pass filters are needed in the output of each stage to insure that the signal source output frequency spectrum does not include subharmonics. Similarly, if an active control loop, i.e., an automatic frequency control or automatic phase control loop, is used in generating the signal, then the loops should be configured to eliminate subharmonic products [25].



(A) Direct Modulation



(B) Up Converter

Figure 1. Block Diagram of a Transmitter.

Modulator circuits are potential sources of undesired signals in transmitters because of their inherent nonlinearities. The carrier is modulated, i.e., the information-carrying sidebands are added, by one of several different methods depending on the particular application. For example, radar pulses are generated by turning modulators, power amplifiers, etc. on-and-off while communications transmitters are modulated either by direct modulation of the frequency source or by the use of an up-converter. (Most up-converters are similar to mixers except the desired output is the sum frequency rather than the different frequency; therefore, for electromagnetic compatibility design considerations refer to Section 3.7.2 of this Handbook.) If other design considerations permit a choice, then for electromagnetic compatibility the modulation technique should be chosen such that the smallest number of undesired signals are generated [26] [27]. Regardless of which type of modulation is used, the transmitter designer must be aware of the undesired output signals which are likely to result from the modulation technique chosen so that adequate interference control and reduction methods can be applied.

The power amplifier and output filter circuits in a transmitter also require careful attention to electromagnetic compatibility considerations. In many instances achieving the transmitter performance goals for these circuits is a real challenge; however, realizing performance goals at the expense of compatibility goals will only create problems during later stages of the transmitter design. The designer must keep in mind both goals throughout the design of the transmitter.

The following guidelines are provided to assist in the electromagnetically compatible design of transmitters:

- Direct generation of the carrier frequency is preferred to generation through multiplication of a low frequency source.
- If frequency multiplication is absolutely necessary, use the highest possible fundamental oscillator frequency to minimize the order of multiplication.
- Use multiple tuned circuits between all frequency multiplication stages.

- The power amplifier should not be used as a frequency multiplier.
- Operate the oscillator at as low a level as possible, then amplify the output if necessary.
- Assure that oscillator circuits are decoupled from both input signal circuits and output power stages.
- Provide shielding between all stages and decouple RF paths to keep spurious signals from reaching the power amplifier.
- If a mixer is used in the generation of the carrier frequency, reduce spurious signals through the use of multiple tuned circuits in the mixer and driver ouput.
- Maintain the frequency and phase stability of the transmitter carrier as high as practicable.
- Use suitable filters at the oscillator output to reduce the noise resulting from oscillator jitter.
- Keep transmitter bandwidth to the minimum consistent with overall system requirements.
- Reduce modulation splatter by limiting the modulating frequency range to the minimum amount required for information transfer.
- Use clippers or AVC to prevent overmodulation or excessive deviation and use filters to remove harmonics from the output signal.
- For pulse systems, use appropriate pulse shaping and well designed switching devices to limit the spectrum width.
- Restrict nonlinearities in the power amplifier.
- Select the operating angle of the output amplifier stage to reduce the number and magnitude of spurious signals.
- Use well balanced push-pull outputs.
- Limit tank circuit parasitic oscillations.
- Use double-tuned tank circuits in preference to pi-section tank circuits for output-to-antenna coupling.

- If additional filtering is necessary for further harmonic suppression, exercise care to ensure that the filters do not exhibit unexpected spurious passbands.
- Completely shield the antenna coupling circuit.
- Do not use nonlinear elements in the antenna circuit.

3.7 Receivers

Communications, radar, and navigational aid systems at FAA facilities contain many superheterodyne receivers such as the one illustrated in Figure 2. From the design viewpoint of this Handbook, these receivers consist of preselector, mixer (down converter), local oscillator, and IF amplifier [28] functional units. Other functional units which might also be a part of superheterodyne receivers--power supplies, amplifiers for low level signals, control units, etc.--have design guidelines presented in other subsections of the Handbook.

Individual preselector, mixer, local oscillator, and IF amplifier functional units must comply with both performance and compatibility design objectives in order to function reliably in the electromagnetic environment at FAA facilities. It is also important that these functional units operate collectively as compatible and reliable receivers. This dictates a knowledge and understanding of the electromagnetic interactions that occur between functional units of receivers. Knowledge and understanding of these interactions can be gained by viewing the electromagnetic compatibility of receivers in terms of three categories of signals, i.e., co-channel, adjacent channel, and out-of-band signals [29].

Co-channel signals are those signals which effectively occupy the same frequency channel as the desired signal. The desired signal is assumed to be comprised of a carrier and modulation sidebands which contain the information. Depending on the type of receiver, the in-band interfering signal may be attenuated by no more than 1 to 3 dB as it passes through the preselector. Signals encountered in this manner may either be similar signals generated at other sites by similar equipment or spurious signals generated by equipments that operate with their fundamental output signals at alto-

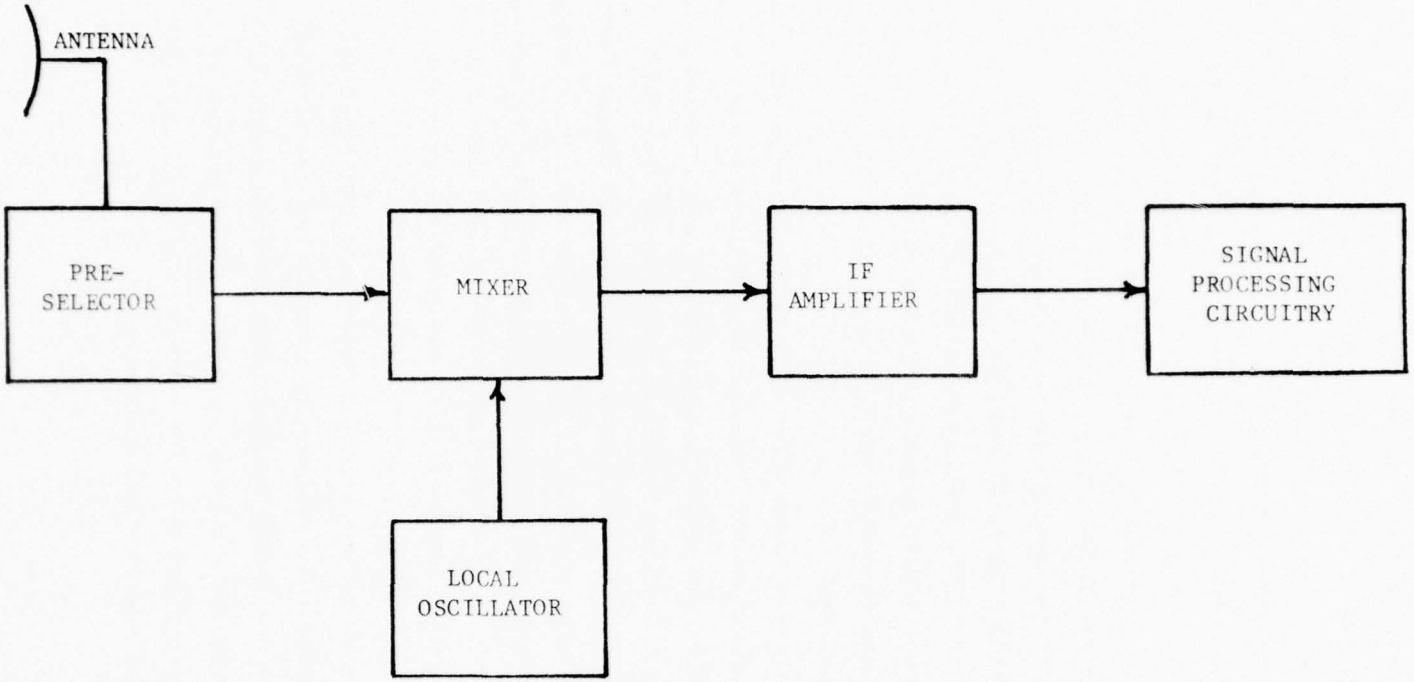


Figure 2. Block Diagram of a Superheterodyne Receiver.

gether different frequencies. Electromagnetic compatibility for co-channel interference is achieved primarily by frequency coordination. For example, prior frequency coordination is required by the Federal Communications Commission (FCC) of all microwave common carrier applications [30]. This coordination is based on equipment location, antenna radiation pattern, transmitted signal level, etc. The purpose of this coordination is to insure by design that similar equipment, being used for similar purposes, will not produce harmful interference at any of the receiver locations. However, this coordination is not applicable to spurious radiations from a nearby transmitter operating at some different frequency. Thus, electromagnetic compatibility in the co-channel case must be achieved by frequency coordination among licensed users and determination, usually by measurement, that the location is sufficiently free (or that it can be made free) of spurious emissions.

Adjacent channel signals are those which fall outside the preselector passband but within the stopband of the preselector. These signals are rejected as a function of the preselector characteristic which varies from the passband edge value (1 to 3 dB) to values as large as 80 dB. This 80 dB value is often used to distinguish between the adjacent channel and the out-of-band rejection characteristics of the preselector. The sources of adjacent channel interference are primarily signals generated by similar equipment in nearby locations. Electromagnetic compatibility is achieved in part by frequency coordination and in part by the preselector characteristic.

Out-of-band signals are those which fall outside the co-channel and adjacent channel signal regions. Generally, the preselector out-of-band characteristic is considered to provide at least some minimum amount of rejection and the rejection is not frequency dependent. The sources of out-of-band signals are numerous and normally have no readily discernible relationship with the type of receiver being considered.

3.7.1 Preselector

The use of preselectors in superheterodyne receivers is an example of achieving electromagnetic compatibility goals by design. Pre-

selectors are often used to reject the image frequency response, to reject adjacent channel signals, and to establish the RF portion of the input noise bandwidth of receivers. Each of these (image response, adjacent channel signals, and wide-band noise) is an unwanted source of energy or spurious emission as far as the receiver is concerned. The purpose of the preselector is to reduce the receiver's susceptibility to interfering signals. Depending upon the specific application and frequency of operation, the preselector may include active stages of RF amplification. The noise figure of the receiver can be improved by using active stages in the preselector. If RF amplification is used to improve receiver response to low level signals, then careful consideration must be given to the response of the preselector and amplifier stages to high level out-of-band and adjacent channel signals. High level signal inputs to RF amplifier stages frequently overload the amplifier and lead to the generation of spurious signals. These spurious signals may not only cause interference, but may also alter the performance of the amplifier such that it does not perform as intended and the effective minimum received signal level could be worse than it would be without RF amplification.

The magnitude of the rejection available to unwanted signals in a preselector is a function of the number of stages, the passband insertion loss, the width of the passband, etc. The desired objectives of a narrow-band, high rejection level preselector for adjacent and out-of-band signals combined with the desired low loss passband characteristic for the intended signal are often in direct conflict with network theory [31].

Major attention in the design of preselectors is often directed toward the passband and adjacent channel regions; however, the out-of-band region is also very important. Higher order passbands may be the result of the circuit design or of stray capacitance and inductance developed across long component leads, etc. Examples of practices to follow in the design of a preselector, therefore, include using components which maintain their characteristics over wide frequency ranges and selecting components with minimum lead lengths.

3.7.2 Mixer

The purpose of the mixer in a superheterodyne receiver is to convert the desired RF input signal energy to IF energy. The RF signal and the local oscillator signal are combined in the nonlinear mixer to produce sum and difference frequency signals of the two original signals. Signals are also produced at many other frequencies and include sum and difference frequencies involving the RF signals and signals which are harmonically related to the local oscillator frequency [32]. One of the sum and difference frequency signals is selected as the IF signal; therefore, only one of the many signals generated by the mixer is desired. In terms of energy sinks and sources, electromagnetic compatibility is achieved by designs that provide energy sinks for all the signals produced by the mixer.

Balanced mixers are frequently recommended over single-ended mixers [33]. Elimination of local oscillator noise, lower oscillator power requirements, local oscillator RF isolation, etc. are some of the advantages of using balanced mixers. When electromagnetic compatibility goals are to be met by design, the local oscillator power required, the available isolation between the local oscillator and RF ports of the mixer, etc. must be known in tangible terms. For example, from an electromagnetic compatibility viewpoint, it might be necessary to reduce the level of the local oscillator signal available at the RF input to the receiver to a level of -100 dBm. The local oscillator input level to the mixer might be 0 dBm; thus the desired cancellation of the local oscillator signal in the mixer is 100 dB. If the mixer designer believes that local oscillator feedthrough in the mixer has been effectively eliminated when 20 dB of isolation is offered, then the receiver designer must be made aware that the preselector has to offer at least 80 dB of additional rejection at the local oscillator frequency.

The IF signal is either the sum or difference of the RF input and the local oscillator signal. Each of these signals is comprised of the carrier frequency and modulation sideband signals, including noise sidebands. Local oscillator noise is converted to IF noise just as RF input signal noise is converted to IF noise. The fundamental performance of the receiver is improved as local oscillator output noise is reduced.

The use of a mixer configuration with reduced local oscillator power requirements reduces the potential for interference in several ways. The receiver power supply requirements are reduced because less local oscillator power is required. If less local oscillator power is available, then there is less potential for interference caused by local oscillator radiation. The magnitude of each of the signals generated in the mixer is related to the magnitude of the local oscillator signal. The magnitude of these higher order responses normally follows a power series function and consequently decreases in level rapidly with reduced local oscillator drive [34]. However, the mixer conversion gain is also a function of local oscillator drive level, and a sufficient level must be provided to produce the required conversion gain.

3.7.3 Local Oscillator

The desired output from the local oscillator in a typical superheterodyne receiver is a single frequency signal. Oscillators designed to produce only one frequency as contrasted to a design that involves selecting one out of many frequencies are preferred; however, operational requirements may dictate the use of a highly stable oscillator. If a crystal oscillator followed by a multiplier chain is used to generate the local oscillator signal, then high pass filters are needed in the output of each stage to insure that the local oscillator output frequency spectrum does not include subharmonics [35]. If an active control loop, i.e., one with automatic frequency control or automatic phase control, is used in generating the local oscillator signal then the loop should be configured to eliminate subharmonic products. Such a control loop might be built around the crystal oscillator/multiplier chain or it might be configured to cause the local oscillator to track or follow the received signal. The total error signal in such circuits will modulate the oscillator. The total error signal fed to the oscillator is comprised not only of the output from the phase detector or discriminator but also any other signals that have been coupled into the control loop [36].

Many oscillators can be modulated by changing the level of the input power (voltage or current); therefore, power supply inputs to the oscillator

should be well regulated and filtered. Power supply input filtering should serve dual purposes--to prevent modulation of the local oscillator caused by the pick-up of signals on the power supply leads and to prevent coupling of the local oscillator signal to the power supply leads and then to the surrounding area. Signals that are harmonically related to the fundamental output of the local oscillator should be eliminated just as subharmonic signals are. Even though signals which are harmonically related to the local oscillator fundamental signal may be generated in the mixer, it is helpful in achieving electromagnetic compatibility goals to eliminate the harmonic output of the local oscillator by filtering.

The local oscillator output, except that portion of the fundamental output which is coupled to the mixer, is a source of undesired signals to every circuit and equipment.

3.7.4 IF Amplifier

The desired characteristics of the IF amplifier are determined by the intended use of the receiver and by the characteristics of other receiver functional units. The gain, bandwidth, noise figure and overload characteristics of the IF amplifier are determined primarily in terms of the expected input signal characteristic. The IF amplifier must frequently handle low level signals; accordingly, component layout, routing of conductors, power supply filtering, method of shielding, etc. are important considerations in minimizing the effects of adjacent channel and out-of-band signals.

As part of a superheterodyne receiver, there is an IF bandpass characteristic which maximizes the output signal-to-noise ratio [37]. It is important to study this characteristic in terms of the expected co-channel and adjacent channel signal levels and perhaps make slight changes in the bandpass characteristic that do not affect the fundamental performance significantly but make the receiver far less susceptible to adjacent channel interference. The out-of-band rejection characteristic is very important in achieving electromagnetic compatibility goals by design. Higher order IF amplifier passbands serve no useful function in the fundamental operation of the receiver; therefore, insuring that higher order passbands do not

exist by providing ample higher frequency bypassing may eliminate undesired receiver susceptibility. The amplifier response to high level signals should be known; the AGC, if used, loop response time should be defined in terms of desired signal characteristics as well as the nature of the expected electromagnetic environment.

There may be little or no choice in choosing the IF frequency [38]. In cases where there is a choice, consideration of the electromagnetic environment should be one of the major selection criteria. For example, if the receiver under development is to be used adjacent to television transmitters which operate on either channel 2 or 3, obviously a 60 MHz intermediate frequency should not be chosen.

3.7.5 Design Guidelines

The preceding discussion concerning the design of receivers to be used in FAA facilities presented an overview of design concepts from an electromagnetic compatibility point of view. As the functional objectives of receivers are reviewed, an emphasis should be placed upon expanding these design concepts to assure equipment designs which not only meet performance goals and operate within the existing electromagnetic environment, but also do not create additional electromagnetic pollution. The following guidelines are design reminders of specific techniques that should aid in realizing this emphasis:

- Remember that coupling between internal and external circuits is the major factor influencing receiver susceptibility. Coupling is affected by component placement, wiring isolation, circuit shielding, signal line filtering, and power line filtering.
- In the basic design, provide adequate RF selectivity through the use of well designed tuned circuits and reduce stray coupling around the tuned stages.
- Add, if necessary, low-pass filters to eliminate high frequency spurious passbands in the preselector.

- From the outset of design and layout, plan for the shielding of the receiver and its critical circuitry.
- Recognize that the degree of internal shielding required to merely permit a receiver to operate without oscillation or instability is not normally adequate to meet EMC requirements.
- House each stage of a receiver from the antenna through the second detector in individual compartments with only those conductors required to carry necessary signals routed between the compartments.
- Route power, AGC, etc. separately to each compartment and filter at the point of entry into the compartment.
- Adequately bond together the sections of a shielded compartment and bond the compartment to the chassis.
- Wherever practical, electrically isolate the mechanical tracking linkages between the various tuned stages.
- Reduce penetrations of the shields between stages to the minimum required for interstage signal coupling.
- Arrange circuits to minimize lengths of signal leads between stages.
- Isolate, physically as well as electrically, the local oscillator circuitry from the RF amplifier stage.
- Ground the shield of coaxial cables, either by means of an RF connector or by connecting the shield directly to the chassis, at the point of penetration, when entering or exiting a shielded RF stage.
- To secure a high image rejection ratio, make the intermediate frequency as large as other considerations will permit.
- Check the RF tuned stages for possible spurious resonances.
- Keep RF gain as low as possible commensurate with the desired receiver noise figure.
- Make RF and IF bandwidths as narrow as operational considerations will allow.

- Keep the number of conversion stages as low as possible.
- Check the levels of local oscillator harmonics in the breadboard stage and take the measures necessary to reduce them.
- If the local oscillator is derived from a low frequency synthesizer, use the lowest possible order of multiplication.
- Provide multiple tuned circuits or bandpass filters to prevent undesired harmonics of the local oscillator frequency from reaching the mixer.
- Shield all oscillator or multiplier stages.

3.8 Digital Units

An increase in the use of digital equipment in data processing, control, and communications systems is the present trend in many FAA operations. The ARTS system and the Common Digitizer are two important examples of this trend. Thus, a thorough understanding of the differences in digital and analog equipment is needed to achieve electromagnetic compatibility. Signals in analog equipments are smooth, continuous voltage or current waveforms, but signals generated and/or processed by digital equipment are binary type waveforms changing between one of two states [39] [40]. In addition, the transition time between states of a digital signal is usually small, i.e., fast risetime. Because of these and other differences, the emission and susceptibility characteristics are different for digital and analog equipments. Therefore, electromagnetic compatibility guidelines for analog equipment normally do not apply to digital units. For example, signal waveforms in analog units may be "smoothed" by filtering to produce the required bandwidth and corresponding frequency spectrum. Most digital units by contrast operate because a signal with a predetermined risetime reached or exceeded a particular threshold level at a specified time and, thus, digital signal filtering for electromagnetic compatibility is usually avoided.

In many complex systems, digital and analog equipments are both integral parts of the entire system. Also, it is important to note that some equipments contain both digital and analog functional units. For these reasons, the designer is reminded that the digital and analog functional units must

exhibit inter- and intra-equipment compatibility. For example, analog functional units must be protected from the "pulses and spikes" associated with the digital functional units. In a similar manner, electromagnetic compatibility techniques must be employed to prevent digital functional units from responding to signals and transients produced in analog functional units.

The designer of a digital unit is concerned primarily with signal switching and timing, i.e., the changing from one state to another and the risetimes between such states. From an electromagnetic compatibility point-of-view, the digital designer must be constantly aware that the risetime, pulse width and the pulse repetition rate of digital signals determine their frequency specturm [41]. Hence, the speed of the digital functional units in addition to the circuit elements used in the unit determine the range and degree of shielding and interunit filtering necessary to control emissions from and susceptibility of the digital unit. Selection of the master clock rate, the associated processing circuits, and in computational units, the core storage arrangements must be based not only on equipment performance goals but also on electromagnetic compatibility goals.

The following guidelines are presented to assist the digital functional unit designer:

- To limit the generation of unnecessary high frequency components, design pulse waveforms to have the slowest rise and fall times which will permit reliable circuit operation.
- Avoid the generation of unnecessarily high logic levels.
- Use the minimum clock rate commensurate with desired operation.
- Avoid clock rates that are integrally related to other system functions.
- Prevent the coupling of data pulses to dc power buses through filtering or secondary regulation.
- Route digital circuit input and output lines separate from power and control leads.

- Everywhere possible, couple out of and into digital circuits at a low impedance point or provide impedance-transforming buffer stages.
- Restrict the generation of switching spikes and minimize overshoot and ringing.
- Use shielded pulse transformers.
- Decouple supply and control leads to prevent interference [42].
- Avoid the use of long, unshielded signal lines.
- Use coaxial, "microstrip", or other shielded lines to transfer pulse signals between circuit boards or between equipments.

3.9 Electromechanical Units

Electromechanical functional units consist primarily of switches, motors, and solenoid-operated components such as relays. FAA electromechanical units include equipment such as teletypes, mechanical modulators, operations monitoring alarms, and motors of all types and sizes. To control emissions from such units, designers must be aware of the transients and other undesired signals that may be produced. Undesired signals are produced in electromechanical units by the rapid switching of currents through inductive loads including relay coils, by relay bounce, and by the brush action of motor commutators. These signals can then be coupled to other nearby equipment via the power and control leads and by radiation from the electromechanical unit itself. Thus, the designer must devote careful attention to the filtering and shielding of all leads entering and leaving the unit and to the shielding provided by the enclosure. The guidelines presented for control and digital units in Sections 3.3 and 3.8, respectively, are for the most part applicable to electromechanical units and should be reviewed by the designer. Portions of two references present design information specifically related to electromechanical units. This information is on pages 218 through 219 and 3-343 through 3-363, respectively, of references [2] and [3].

IV. MECHANICAL DESIGN

4.1 Broad Guidelines

Mechanical design guidelines in this Handbook differ from electronic design guidelines in that they are concerned almost exclusively with signal coupling paths as opposed to either signal sources or sinks. As such, mechanical design for electromagnetic compatibility involves path-related guidelines for shielding, filtering, grounding, chassis and enclosure construction, circuit layout, cables, compartmentalization, etc. [43].

The broad design guideline of primary importance at this point is the fact that rigorous attention to compatibility during electronic design efforts in no way alleviates the necessity of equally rigorous attention to compatibility during mechanical design efforts. Too often, functional units are designed, constructed on breadboards, and modified until desirable performance is achieved. Then, in the transition from breadboard to final packaging, interference control techniques are either ignored or compromised to the extent that the end-product is incompatible with its operational environment. It is therefore essential that adequate mechanical design guidelines be known and incorporated if electromagnetic compatibility and operational reliability are to be achieved. If compatibility and reliability are achieved in a cost-effective manner, the guidelines must be incorporated during initial equipment construction and fabrication. Costly and time consuming retrofits will thereby be avoided.

4.2 Functional Subunit Layout

The layout of circuit elements and signal paths within functional subunits must be designed such that undesired intercoupling of signals is minimized [2] [3]. This is particularly true in instances where circuit elements and signal paths are necessarily in close proximity to each other, such as on printed circuit boards. The layout of signal paths within functional subunits involves many of the same design guidelines subsequently presented in Section 4.5 for cabling between functional subunits. Specific

design guidelines applicable to functional subunit layout are as follows:

- Do not route low level signal paths adjacent to either high level signal paths or unfiltered power supply conductors.
- Avoid the use of long parallel conductor runs on printed circuit boards simply because they are "pretty".
- Where long parallel runs cannot be avoided, e.g., on "mother boards", arrange conductor functions in order across the board from the lowest level sensitive circuits to the highest level circuits. Filtered dc power conductors and low-rate control function conductors (potentiometer leads, reference voltages, etc.) may be routed in the middle of the board.
- Assign circuit functions on printed circuit boards following the principle of physically separating sensitive networks from high level or transient-producing networks.
- Arrange circuit functions to minimize the lengths of signal conductors.
- For RF and high speed digital paths, consider the use of a double sided board and microstrip transmission lines properly matched to the terminal impedance [44].
- Insure that excessive conductor parallelism does not exist between adjacent boards.
- Place suppression filters as close as possible to undesired signal sources and susceptible circuits. As a minimum, position the filters on the same board with the undesired signal source or susceptible circuit.
- For dc-to-dc converter layout, place switching elements (transistors, SCR's) and rectifiers as close as possible to the transformer to minimize conductor lengths.
- Place regulating elements and filter capacitors as close as possible to the rectifier diodes.

- Consider carefully the position of transformers and inductors on adjacent boards to assure that undesired magnetic coupling does not occur.
- Orient the winding axis of adjacent transformers at 90° with respect to each other to minimize coupling due to the concentration of leakage flux along the winding axis and, hence, to minimize the required shielding.
- Effectively ground large unetched portions of printed circuit boards and utilize these ground portions as shields.
- Particularly on high speed pulse circuit boards and RF circuit boards, leave as much "ground plane" as possible.
- Ground any shields on printed circuit boards directly to the main chassis independent of any grounds located on the board.
- Exercise care in placing shields close to cricuits in which the circuit Q is a critical factor because losses in the shield may lower the circuit Q.
- Shields on printed circuit boards should not be used as a signal return conductor since currents on the surface of the shield provide a source of undesired radiated energy.
- When using bypass capacitors for interference reduction purposes, ground the metal cases directly to the chassis, either by suitable clamps or by threaded-neck type construction.

4.3 Compartmentalization

Compartmentalization of common circuitry types within functional units or equipment can provide a means of containing undesired signals within bounded areas. These bounded areas are chosen such that undesired signals are effectively decoupled from potentially sensitive conductors or circuits. Therefore, the mechanical design of functional units and equipments should include compartmentalization for isolating the path of undesired

signals [45]. Guidelines for design of such compartments are:

- Use modularized construction where possible; in particular, locate power line input filters, high signal level circuitry, and low signal level circuitry in shielded compartments.
- Circuits capable of producing high level interference signals should be isolated in separate compartments from circuits with low signal levels.
- Use intra-equipment shields such as panels or partitions to separate high level sources from sensitive receptors.
- If an equipment's power converter is housed in a separate shielded compartment, route all power source conductors directly into the compartment.
- Circumferentially bond filter cases to the chassis. If the surfaces are aluminum, they should be iridited, never anodized. Mounting ears or studs must exhibit firm and positive contact over the entire area of their mounting surface.
- Provide effective electric and magnetic field shielding of the power supply.
- High voltage power supplies should be adequately shielded and carefully isolated from susceptible circuits.
- Consider the use of magnetic shields that completely surround susceptible circuits as a means of reducing magnetic coupling from the power conductors. Low frequency interference signals such as 60 Hz "hum" can be effectively reduced by this means.

4.4 Chassis and Enclosures

The physical design of chassis and enclosures, i.e., the structural materials and construction techniques, drastically influence the electromagnetic characteristics of functional units and equipments [46] [47]. It can be said without fear of contradiction that the design of chassis and enclosures often determines whether electromagnetic compatibility with operational environments is realized or not. This is true because proper structural

materials and construction techniques can be correctly used to alter the path of most undesired signals within a functional unit or equipment. The use of improper materials and techniques will not only reduce the probability of compatibility, but will also increase the need for intra-equipment devices to manage undesired signals. Consequently, satisfactory design of chassis and enclosures takes full advantage of inherent mechanical opportunities to both realize electromagnetic compatibility and minimize requirements for unnecessary design features. In this manner, equipment reliability and cost are favorably influenced.

Chassis and enclosures are perhaps the most effective means of providing shields for controlling the path of undesired signals within an equipment or functional unit. The extent of shielding is dependent on both the selection of structural materials and the design techniques used in construction. The choice of structural material is dictated primarily by the electromagnetic environment, i.e., the strength of the total field and the relative strengths of the magnetic and electric components of the field, within which equipments and functional units must reliably function. Shielding via design is primarily limited only by the designer's knowledge and ingenuity in designing seams, apertures, penetrations, and bonding for chassis and enclosures.

Specific guidelines by which chassis and enclosure design may provide shielding for the control of signal paths are as follows:

4.4.1 Structural Materials

- Low frequency circuits are generally characterized by currents which provide magnetic fields while high frequency circuits are characterized by voltages that provide electric fields.
- Most materials suitable for chassis or enclosure construction will provide shielding against electric fields. Typical of these materials are aluminum, steel, and magnesium. The predominate shielding mechanism will be signal reflection rather than absorption.

- Shielding against magnetic fields requires ferromagnetic structural materials. Typical of these materials are mu-metal and iron. The predominant shielding mechanism is absorption rather than reflection.
- Intense electromagnetic environments require materials capable of shielding against both electric and magnetic field components; therefore, a structurally sound ferromagnetic material is necessary. The amount of shielding effectiveness will be directly influenced by material thickness as well as the adequacy of electrical bonding and grounding procedures.

4.4.2 Seams

- Mechancial discontinuities must be minimized if leakage radiation into and out of chassis and enclosures is to be controlled.
- Adequately bond chassis and enclosures at every seam and discontinuity to assure that the conductive surface is as homogeneous as possible.
- Remember that the poorest electrical bond will determine the shielding effectiveness of the enclosure.
- Obtain a metal-to-metal contact at seams to prevent leakage and radiation of electromagnetic energy.
- Where possible, seams should be welded, brazed, or soldered such that the joint is continuous; however, where these metal-flow bonds are not feasible, satisfactory results can be obtained in some situations by the use of closely spaced rivets, spot welding, or nuts and bolts. Figure 3 illustrates the typical shielding effectiveness of a seam as a function of screw spacing.
- When bolts or rivets are used to make a bond, apply first at the middle of the seam and then progressively toward the ends

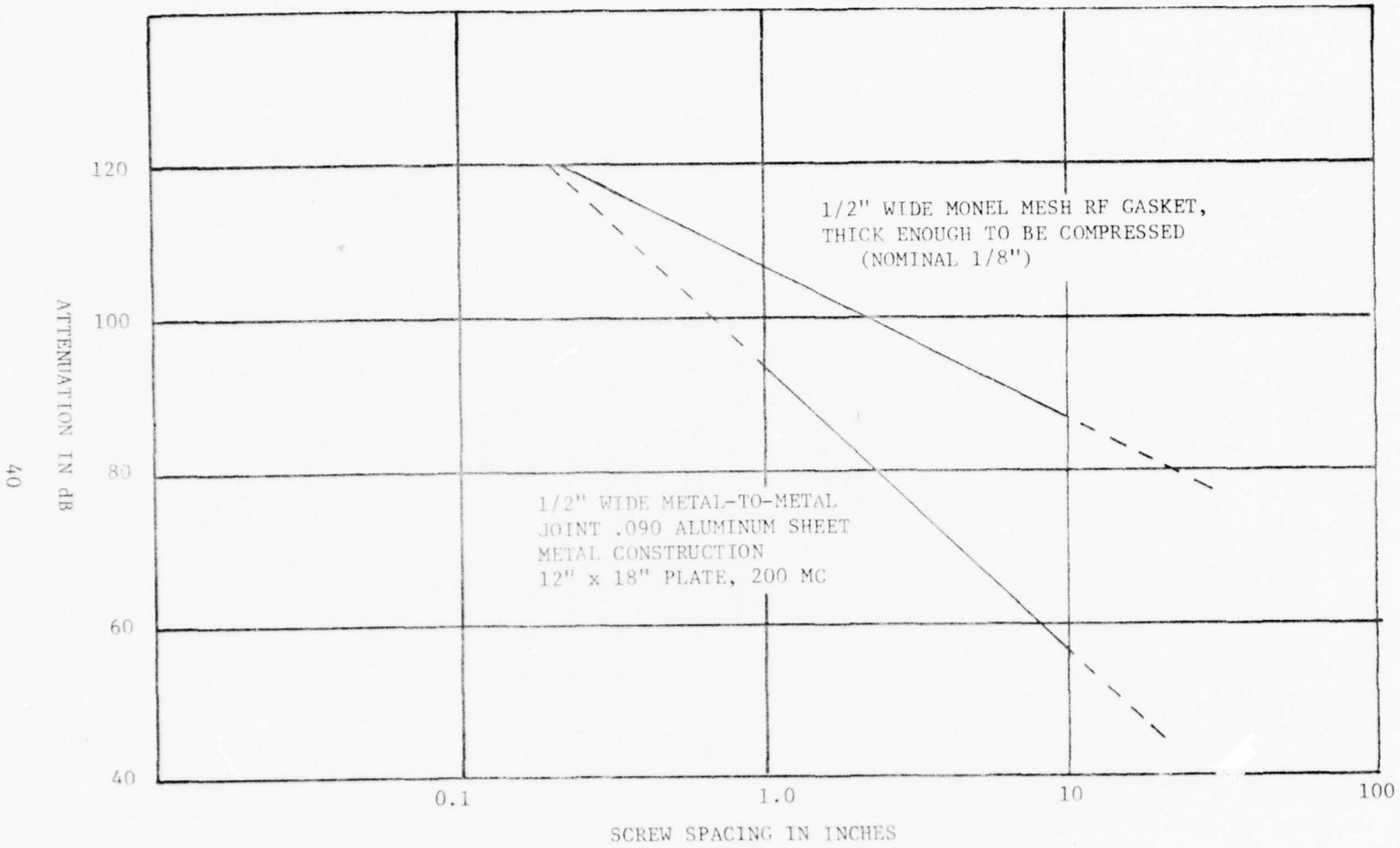


Figure 3. Shielding Effectiveness of Seams as a Function of Screw Spacing [48].

of the seam to prevent the mating surfaces from buckling.

- Provide as much overlap as possible and closely space fasteners to reduce the tendency of a joint to buckle.
- Assure that the fastening method exerts sufficient pressure to hold the surfaces in contact in the presence of deforming stress, shock, and vibration associated with the normal operation of equipment.
- Employ a gasket or finger-stock material where seam uneveness is likely or where removable panels, drawers, etc., are necessary. The gasketing materials should fill gaps and uneven places to provide continuous electrical contact between faying surfaces. Figure 3 also shows a typical increase in shielding effectiveness through the use of gasket material.
- Attach removable covers and panels with closely spaced screws and apply conducting gasketing around the periphery.
- Choose gaskets with properties of high resilience and high conductivity.
- Select gaskets according to their intended use and required characteristics [49] [50] [51].
- Provide the minimum gasket thickness which will allow for the expected surface discontinuities of the joint.
- Provide the appropriate gasket height and pressure necessary to achieve an RF-tight seam. Shielding effectiveness of gaskets improves up to a certain limit with increases in joint pressure as illustrated for a typical tin-plated copper gasket in Figure 4.
- Consider the frequency of use of the joint in selecting the gasket.
- Select gasket materials which are corrosion resistant, conductive, and possess an adequate degree of strength, resiliency, and hardness.

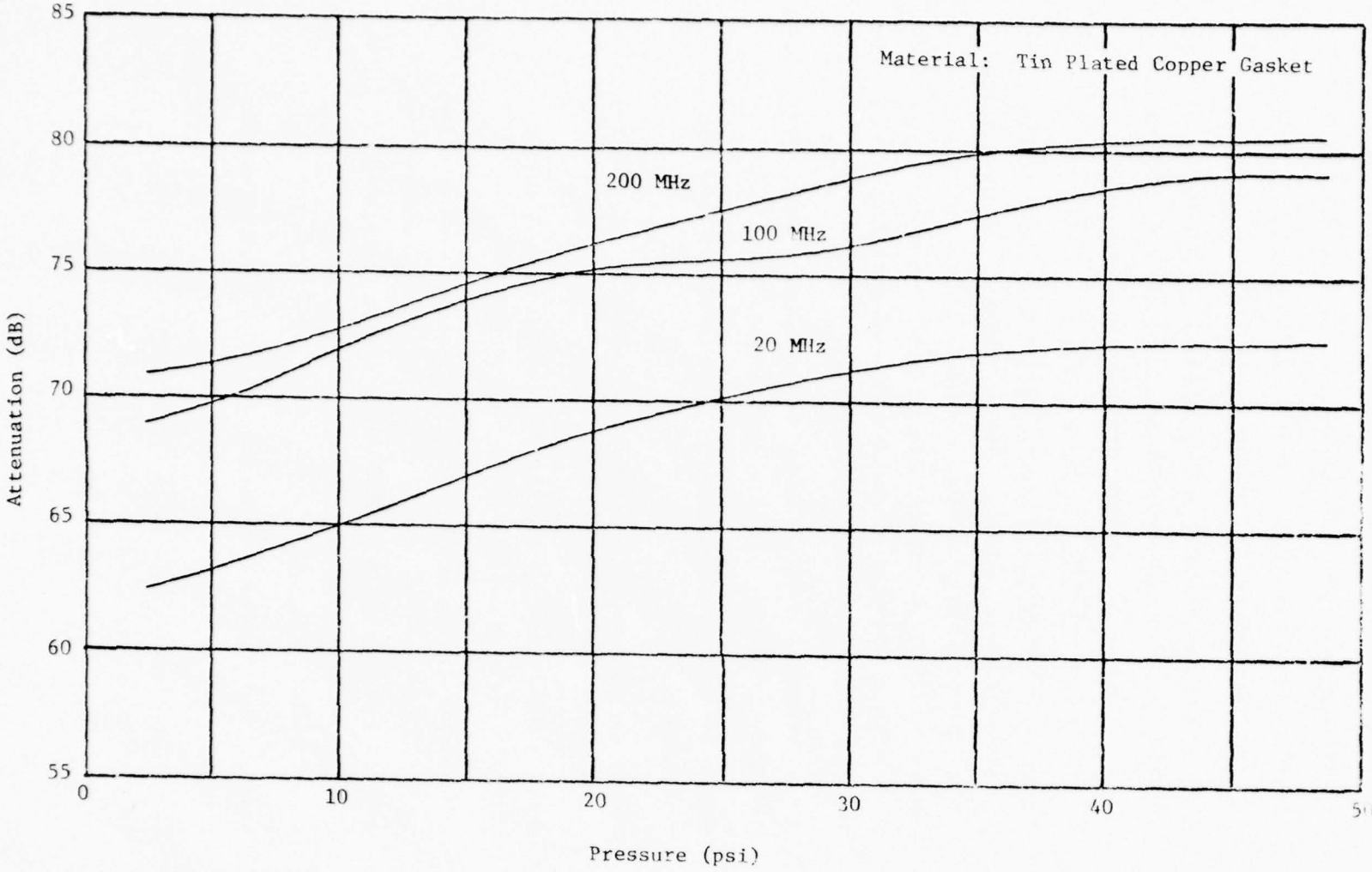


Figure 4. Shielding Effectiveness of Seams as a Function of Screw Spacing.

- Choose gaskets made of hard temper materials to break through any nonconductive surfaces on faying metals.
- Assure that the correct method of mounting gaskets in permanent seams [51] and on hinged doors [53] is employed.
- Assure that the metal surfaces which mate with gaskets are free of nonconductive finishes such as oily film, corrosion, moisture, and paint.
- Use finger stock as an alternative to mesh type gaskets when a sliding type of contact is necessary.
- Handle finger stock with extreme care and install it in a recessed or inner lip to minimize the possibility of mechanical damage.
- Carefully maintain the pressure exerted by the spring fingers because this pressure is highly important to the shielding effectiveness of the seam.

4.4.3 Penetrations and Apertures

- Consider the degree to which the shielding integrity of an enclosure is degraded by cable penetrations. Figures 5 and 6 illustrate the reduction in shielding effectiveness which can occur in a typical enclosure when unfiltered conductors penetrate the shield.
- Route all input power lines into enclosures through filter boxes containing series chokes and bulkhead mounted feed-through capacitors.
- Isolate input and output terminals of power line filters by proper mounting and physical separation.
- Route all control leads into enclosures through filter boxes with series chokes and bulkhead mounted capacitors.

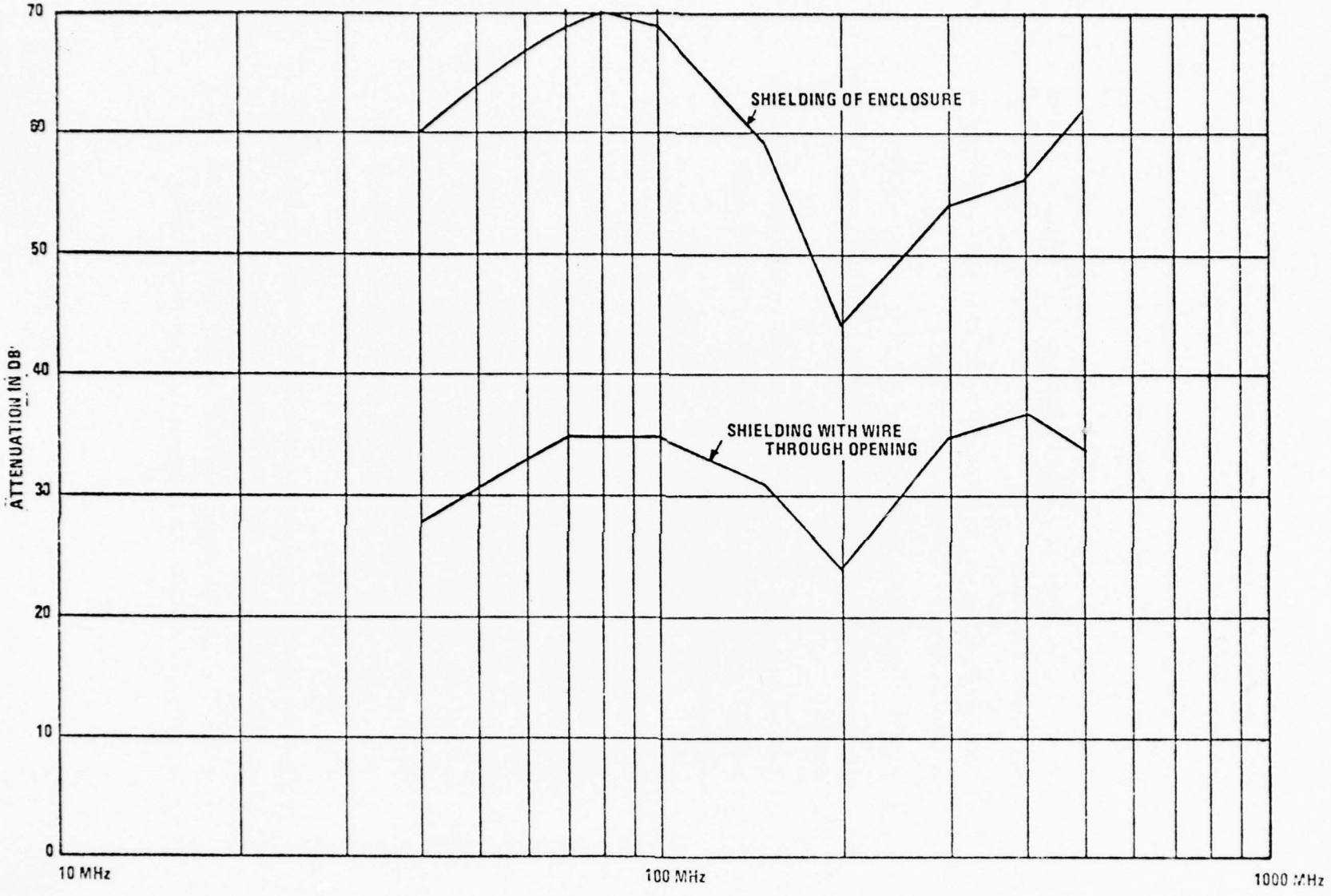


Figure 5. Reduction of Shielding Effectiveness of Typical Enclosure With Unfiltered Wire Through Shield Opening [52].

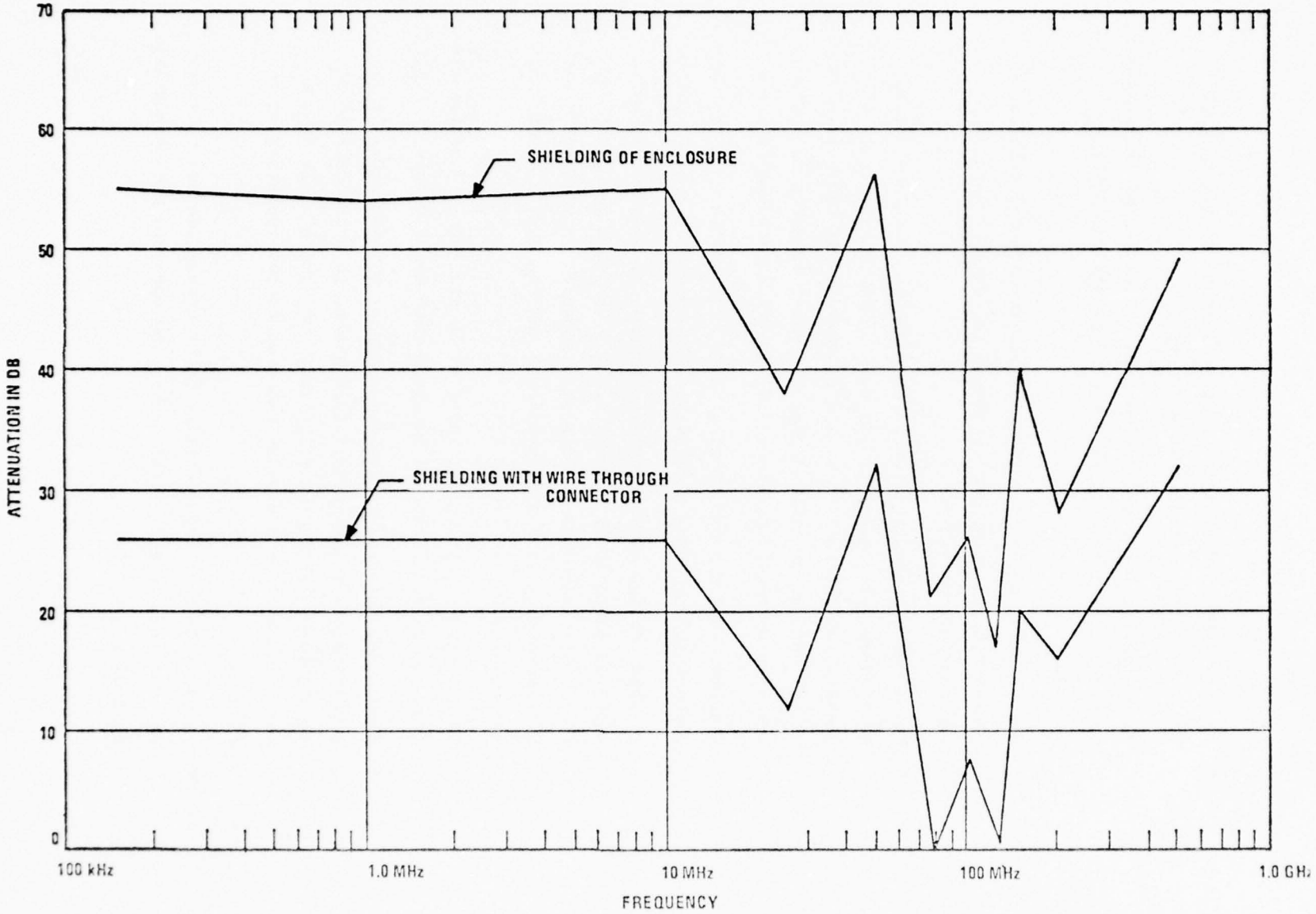


Figure 6. Reduction of Shielding Effectiveness of Typical Enclosure With Unfiltered Wire Through a Connector Pin[52].

- Bypass termination points of control leads to ground except where circuit functions are affected.
- Mount filters for power and control cables inside the enclosure and extend the filter input terminals through the enclosure.
- Use shielded cables for signal lines penetrating shielded enclosures and peripherally ground the outer shield to the enclosure if possible.
- Metal control shafts extending through an enclosure should be grounded with metallic fingers, a grounding nut, or an RF gasket. An alternative to the grounded metal shaft is a nylon, teflon, or other dielectric shaft inserted in a waveguide-below-cutoff cylinder [54] as illustrated in Figure 7.
- Remember that a metal shaft or wire inserted in a waveguide-below-cutoff opening will negate its shielding effectiveness.
- If other design objectives require the use of a metal control shaft isolated above ground, e.g., a variable capacitor control shaft, consider the use of a recessed control shaft with a screw-on cap or a spring-mounted cap lined with a metal gasket as shown in Figure 8.
- Do not permit any control shaft to be electrically continuous from the external control location into an RF module or circuit.
- Keep holes for ventilation or drainage of moisture small in effective electrical area, if possible, to avoid decreasing the enclosure shielding efficiency. A "small" hole is one which is small in dimension compared to the operating wavelength.
- If electrically large ventilation or pressurization openings are required in enclosures, cover the openings with a suitable shielding material.

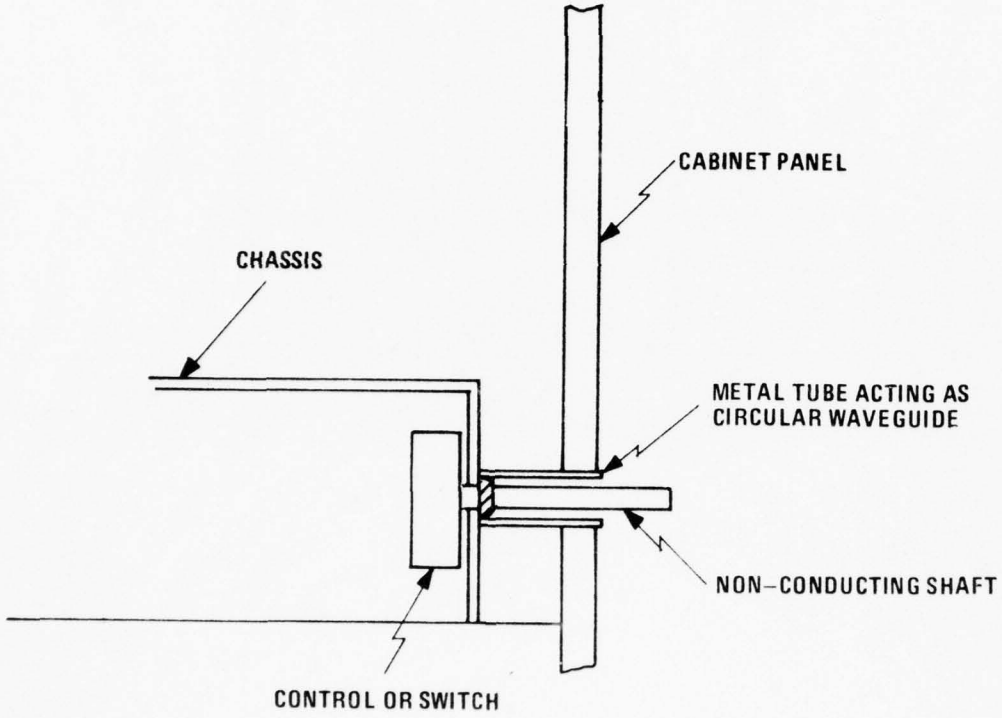
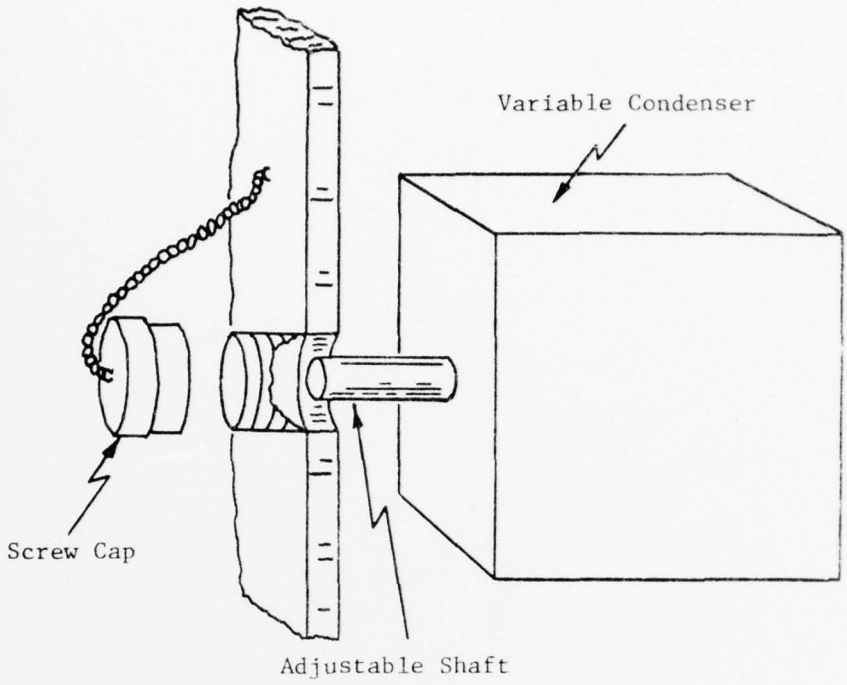


Figure 7. Use of Cylindrical Waveguide-Below-Cutoff for Control Shaft Shield Penetration.



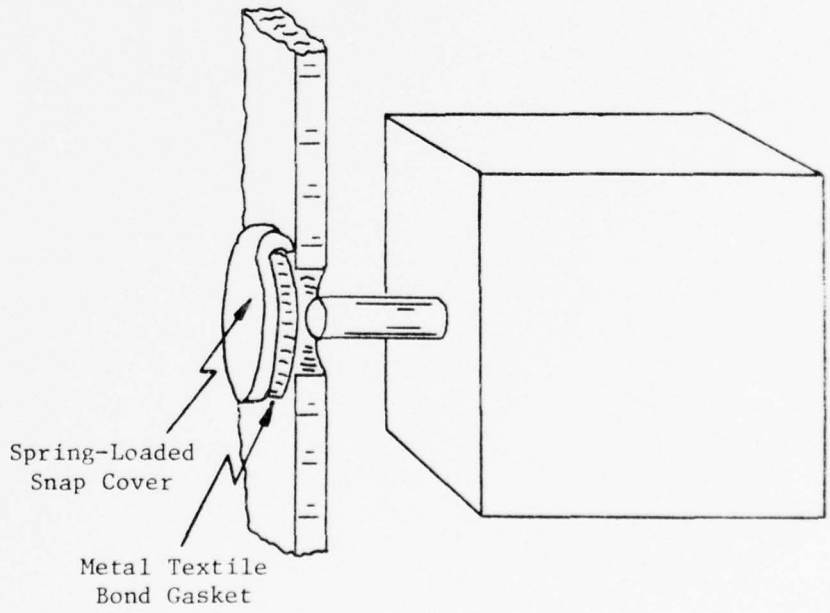


Figure 8. Shielding for Recessed Shafts.

- Keep in mind dissimilar metal effects when selecting the shielding materials (see paragraph 4.4.4).
- Consider the airflow characteristics of any type shielding material that is placed over ventilation apertures. Figure 9 shows the pressure drop to be expected for various types of shielding materials.
- Use honeycomb panels to shield apertures where shielding, ventilation, and strength are important and weight is not a critical factor. Honeycomb panels operate on the principle of a waveguide-below-cutoff [54]. Table 1 gives typical cutoff frequencies for standard honeycomb cell sizes.
- If enclosure design or construction requirements prevent the use of honeycomb, consider the use of layers of copper screening [55]. It should be recognized that screening will provide a lower shielding effectiveness and a higher air resistance than honeycomb.

TABLE 1

Properties of Honeycomb

Cell Size (in)	Cutoff Frequency (GHz)	Recommended Maximum Operating Frequency (GHz)
1/8	48	16
3/16	32	10.7
1/4	24	8.0
3/8	16	5.3

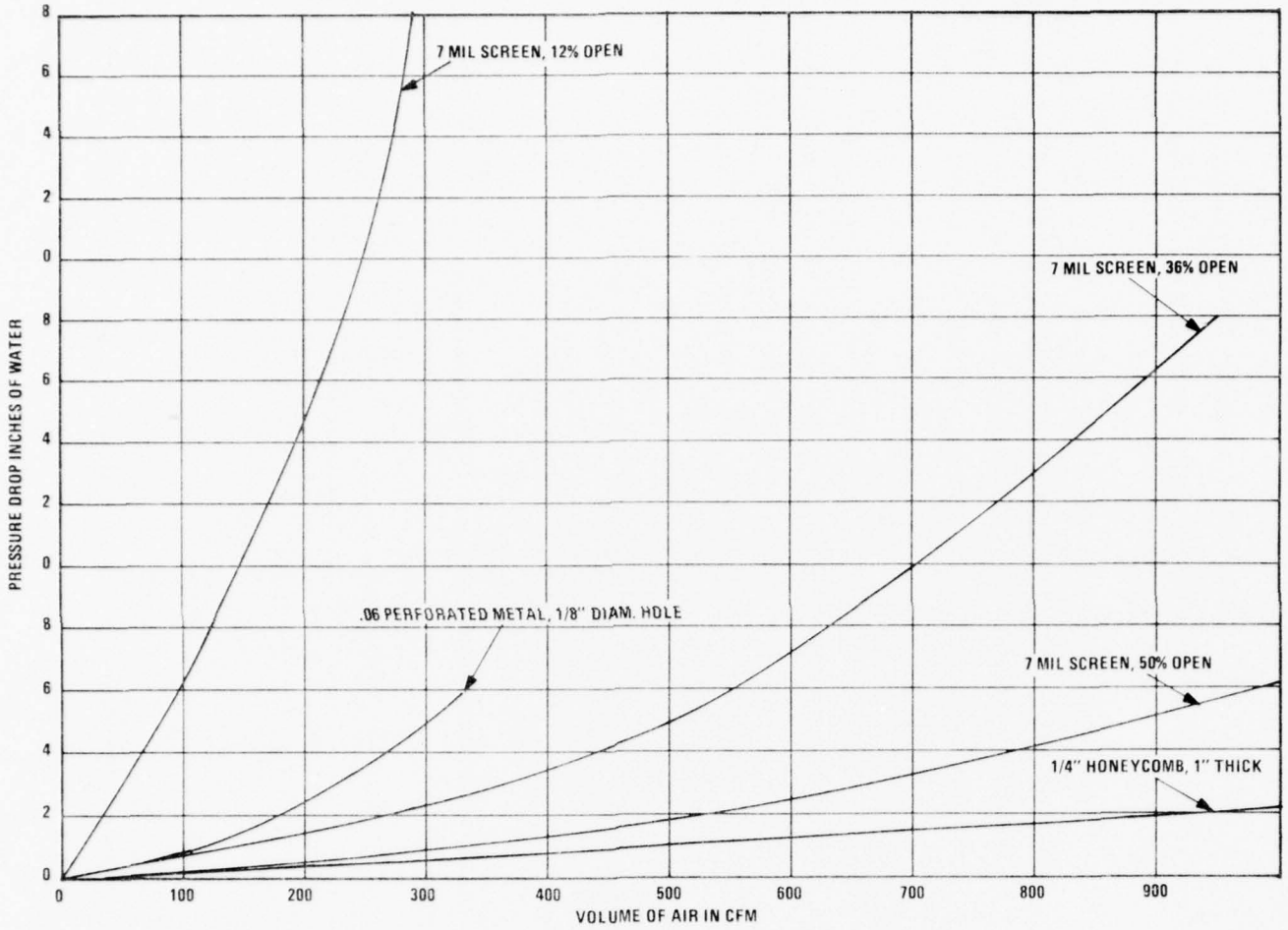


Figure 9. Pressure Drop Versus Air Flow for Various Materials [52].

- Compare the attenuation of the various types of screen with the shielding effectiveness required before choosing the screen to be used.
- Mount screens over apertures in the manner shown in Figure 10.
- Shield meters over the back and filter all leads as shown in Figure 11 if possible.
- An acceptable alternative to shielding the back of meters and filtering meter leads is to shield the front of the meter with a screen or conductive glass made continuous with the enclosure as shown in Figure 12.
- If conductive glass is used, consider the conductivity required to achieve the desired shielding effectiveness. Figures 12 and 13 give the shielding effectiveness of conductive glass as a function of resistance and frequency, respectively. Figure 14 shows the shielding effectiveness of 10 ohms per square conductive glass from 100 kHz to 1 GHz.
- Provide metal caps for fuse receptacles and for phone and meter jacks. Use fuses, jacks, and receptacles that have metallic bodies where possible.
- Use metallic gaskets around each fuse receptacle and each jack.
- Filter the leads and shield the rear or shield the front of pilot and indicator lamps. Shielding of the front may be achieved through the use of wire screen or conductive glass.

4.4.4 Bonding

- Whenever possible, accomplish bonding through the joining of similar metals.
- Consider the relative location on metals in the galvanic series [56] and provide adequate corrosion protection [57].
- Assure that the dc resistance of bonded connections is 0.001 ohm or less.

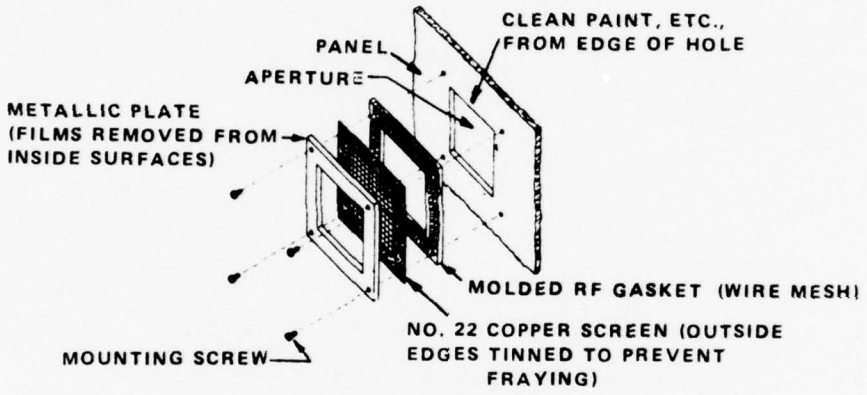


Figure 10. Method of Mounting Wire Screen Over a Large Aperture.

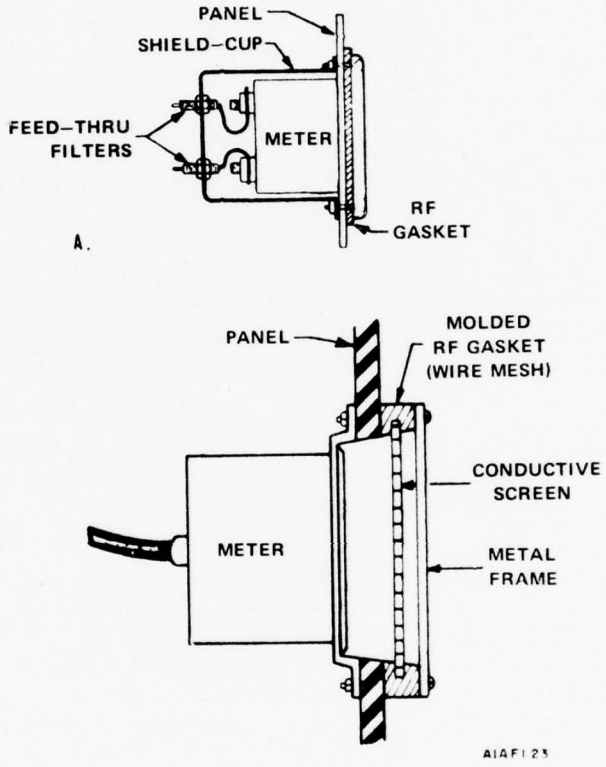


Figure 11. Acceptable Methods of Shielding Panel-Mounted Meters.

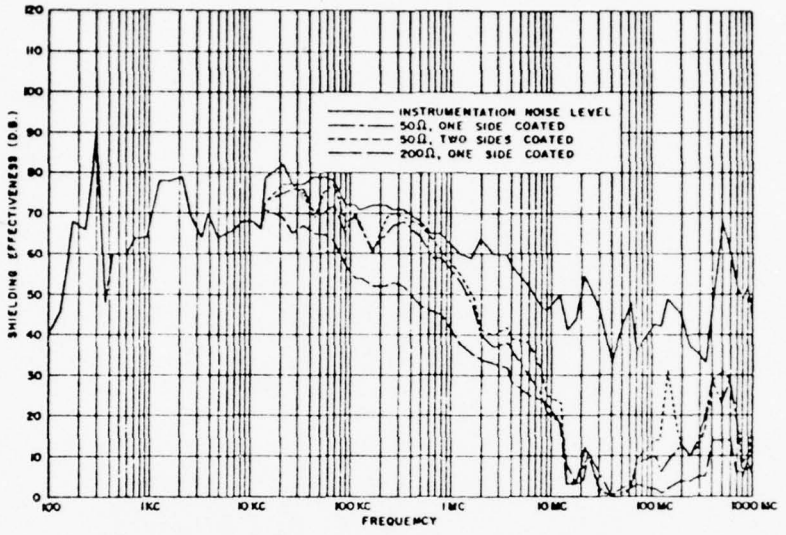


Figure 12. Shielding Effectiveness of Conductive Glass to High Impedance Waves [58].

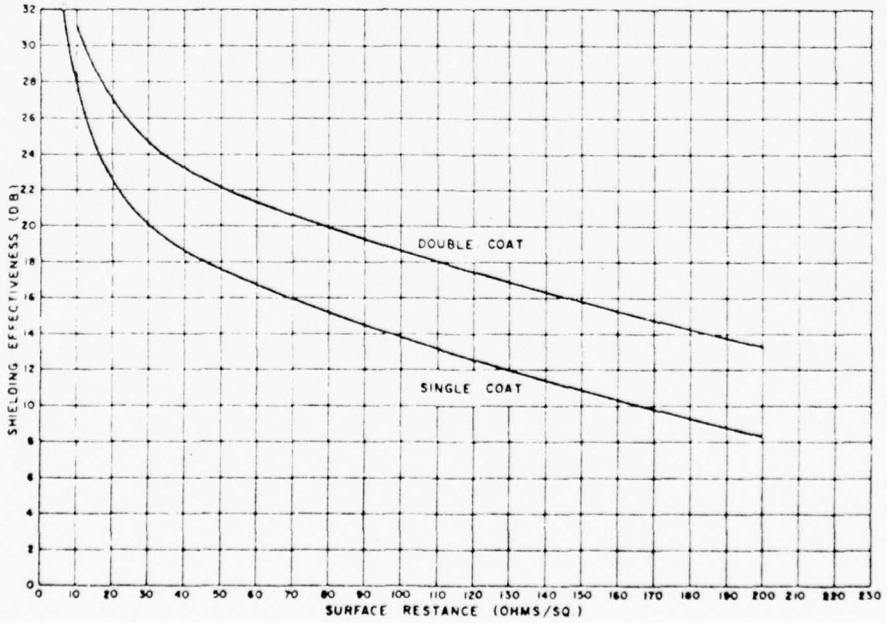


Figure 13. Shielding Effectiveness of Conductive Glass to Plane Wave Propagation [58].

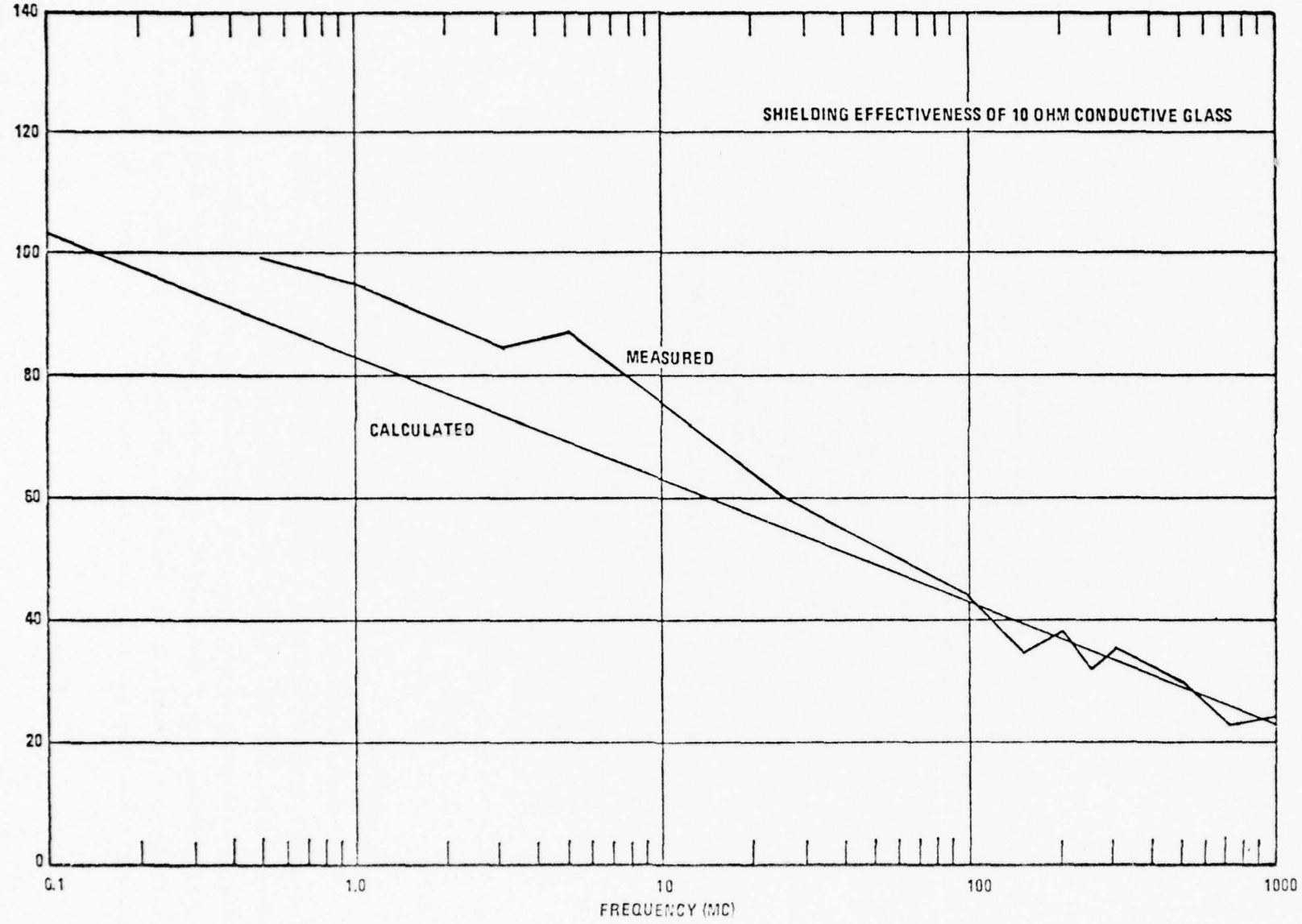


Figure 14. Shielding Effectiveness of Conductive Glass[52].

- Contour mating surfaces so that the maximum contact area is realized.
- Clean all mating surfaces before bonding.
- Remove all protective coatings having a conductivity less than that of the metals being bonded from the contact areas of the two mating surfaces before the bond connection is made.
- When protective coatings are necessary, design them so that they can be removed from mating surfaces. Generally, protective metal platings such as cadmium, tin or silver need not be removed.
- Bond mating surfaces immediately after protective coatings are removed to avoid oxidation.
- Weld or braze all mating surfaces when possible.
- Do not use threads of screws or bolts to establish RF bonds.
- Do not use paint to establish an electrical or RF bond.
- Compress all RF gaskets.
- Seal the periphery of exposed joints with a suitable protective compound.
- Use bonding jumpers only as a substitute for direct bonds. If the jumpers are kept short they can be considered a reasonable substitute.

4.5 Cabling

Intra-equipment cables provide the signal paths between different functional subunits within a single piece of equipment. In recognition of the probable difficulty associated with changing such cables once installed, careful consideration must be given to the design of each intra-equipment cabling system [59]. The specific cable for a particular signal path should be chosen on the basis of the relative level of the signal or relative sensitivity of the terminating circuit, the frequency of the signal, and the

circuit impedance. The cable network should be carefully planned to minimize cable lengths and to effectively segregate high level circuits from low level circuits. Unshielded and unfiltered conductors entering or leaving an enclosure may completely negate previous shielding efforts. Therefore, it is necessary to provide adequate shielding on all conductors which are paths for interference producing currents. Another factor to remember is that the cable shields are an integral part of the equipment grounding system and care must be taken to assure that the integrity of the grounding system is not compromised. The following guidelines are presented to aid in the establishment and maintenance of a compatible cabling system between functional units within equipments:

4.5.1 Cable Selection

- Twist the three-phase wires and the neutral wire in a four-wire, wye-connection to effectively cancel the magnetic field produced by the in-phase third-harmonic currents that flow in each phase.
- Route dc reference circuits as twisted-pairs.
- Route single-phase ac control circuits and reference circuits as twisted-pairs.
- Avoid the use of long, unshielded signal lines if possible.
- Shield all low level, high impedance signal lines.
- Shield all cables that conduct pulses with fast rise or decay times.
- Use shielded hookup wire for high level leads inside the chassis to prevent interference signals from coupling to other internal leads which extend through the chassis.
- Use twisted-pair wires for low frequency cable runs.
- Use shielded twisted-pair where maximum low frequency isolation is required.

- For balanced signal circuits, use twisted-pair or a balanced coaxial line with a common shield.
- For effective decoupling throughout the spectrum, twisted-pair conductors should be enclosed by conventional copper braid shield unless other constraints are imposed.
- Do not use the shield on a low frequency cable for circuit return currents. Two wires should be enclosed within the shield covering to carry circuit currents.
- Use coaxial, "microstrip", or other shielded lines to transfer pulse signals between circuit boards or between equipments.
- Use coaxial cable for transmission of RF, pulsed and other high frequency applications and for other applications where impedance match is critical.
- In all cases, terminate coaxial cables in their characteristic impedance.

4.5.2 Cable Shield Grounding

- Assure that the shields of all low frequency, twisted-pair cables are single point grounded.
- Ground the shields of audio and low frequency circuits at one end only. Use RF bypassing at other end, if necessary.
- Ground unused wires at only one end to prevent ground loops.
- Insulate all low frequency shields to prevent undesired grounding.
- Do not electrically join individual shields together so that one shield carries the RF currents of another.
- For multiconductor twisted-pair cables that have individual shields as well as a common shield, insulate all shields from one another within the cable.

- Take precautions to prevent the exposed portion of a shield from intermittently contacting another uninsulated portion of shielded cable.
- Terminate shields no further than 0.25 inches from the ends of the lines they are shielding.
- Avoid common shield grounds when the shield-to-connector or connector-to-ground lead length exceeds one inch or when circuits that may interact are involved.
- Connect shields to the ground plane by 1.5 inches or less of 0.25- or 0.5-inch wide tin-plated copper strap.
- Remember that the cable RF shield is a part of the complete shielding enclosure and should have no openings.
- For coaxial cables, assure that shields are circumferentially bonded at all connectors.
- Do not use shields for signal returns except in the case of coaxial cables.

4.5.3 Connector Selection and Installation

- Allow for a sufficient number of connectors so that one type of circuit is not required to be routed within the close proximity of another type of circuit.
- Select connector types so as to provide a sufficient number of pins for the required shield terminations.
- Design shield terminations so that the equipment maintenance is not impaired.
- If the circuit design permits cable shields to be interconnected at connectors, terminate such shields through a collectively crimped peripheral ring utilizing two ground wires: connect one wire between the ring and the connector shell and carry one wire through a connector pin.

- Where the circuit design requires isolation of the shields in cables that are routed through multipin connectors, terminate the shields on individual pins. If at all possible, do not gang the individual shields in low frequency cables to a single pin.
- If the cable shields are routed through the connector on separate pins, connect each shield to a pin adjacent to the pin for the associated signal conductors.
- Shield continuity must be maintained at all intermediate connectors and treated in the same manner as in connectors for enclosure penetrations.
- Carefully ground all connector shells to the case through the establishment of high quality bonds.
- Reduce leakage from connectors by proper installation procedures such as making a good bond between the cable shield and the shell of the connector, eliminating all air gaps in the connector, and using connectors built to close tolerances.
- Do not use star-tooth washers between connector shells and the equipment case because the openings between the teeth degrade the shielding effectiveness of the enclosure.
- To prevent electromagnetic leakage around the connector shell, it may be necessary to install an RF gasket between the connector and the equipment case.

4.5.4 Cable Routing

- During initial construction phases, locate wiring to minimize interference coupling between transmission paths.
- To reduce mutual coupling, separate cables from one another and route them away from interference sources and/or susceptible circuits.

- Do not route power and signal circuits through the same connector.
- Separate input and output signal lines; do not route input and output signal lines through the same connector or in the same wire bundle.
- Minimize the separation between a signal wire and its associated return to reduce pickup in the loop.
- Keep both leads of a power circuit wiring run together; avoid loops that encircle sensitive control circuitry.
- Separate input lines from output lines (do not install in same wire bundle or connector).
- Do not bundle reference and susceptible circuits with power and other circuits carrying high level signals.
- Route dc and control circuits in a separate wire group.
- Route susceptible wires away from power supplies, transformers, and other high power devices.
- Do not bundle coaxial cables carrying high level energy with unshielded cables or shielded cables carrying low level signals.
- Route digital signal lines separate from power and control leads.

4.6 Grounding

Grounding is an extremely important factor in the design of electromagnetically compatible functional units and equipments [61]. The implementation of a carefully designed grounding system within equipments will significantly reduce interference signals and will enhance other electromagnetic compatibility techniques. On the other hand, improper grounding techniques can not only produce interference signals but may actually prevent other compatibility techniques from performing their intended functions.

The purpose of signal grounding within functional units and equipments is to provide a common reference level for all signals. The signal grounding philosophy to be used for equipments is primarily a function of operational frequencies and circuit impedance levels. Therefore, equipment

operational modes and designs must be thoroughly analyzed before a grounding philosophy can be selected. This selection must also be such that necessary interfaces with other equipments can be made without compromising their signal ground philosophy or that of the facility.

Whichever ground system philosophy is chosen for the equipment, the following guidelines will assist in providing the necessary low impedance reference level for signals. (For a more detailed discussion on signal grounding and on the proper selection of equipment ground systems, refer to reference [61].)

- To secure a low impedance ground connection keep the ground leads as large and short as possible and bond them directly to the ground plane.
- Ground only one point of any shield used on low frequency (0 to 1 MHz) circuits to the signal reference.
- For longer cable runs, multipoint shield grounding may be more effective than single point grounding.
- To approximate the ideal single point grounding system, use a ground bus or ground plate that is insulated from all cable shields and circuit grounds except at one point.
- Utilize several arterial ground conductors to the signal reference point (not bus) in low frequency equipment.
- Avoid ground loops in low frequency equipments.
- Have as few series connections (solder joints and connectors) as possible in a ground bus and make sure that they are good, solid electrical connections.
- Adequately bond ground structures together to assure that the conducting surface is as homogeneous as possible.
- Connect all statically chargeable conducting surfaces to the basic structure through adequate bonds.
- Adequately bond all connector and patch panels to the ground plane.

- When implementing bonding techniques, always remember that bonding straps do not necessarily provide a low impedance current path at RF.
- For multipoint grounded systems, individual shields may be grounded at different physical points on the ground plane so long as the shields are insulated from each other.

V. LIGHTNING STROKES

Lightning strokes are characterized by multiple short duration discharges that transfer large amounts of electric charge between clouds and earth structures. The fast rise time, high peak amplitude currents that result from these charge transfers repeatedly cause severe mechanical, thermal, and electrical damage to sensitive electronic equipments used in FAA facilities. Since this damage may be either electrical or mechanical in nature and effect components as well, these design guidelines for lightning strokes are presented under this separate heading.

Lightning flashes typically consist of a rapid sequence of events involving an initial discharge followed by a series of two to four subsequent discharges [62]. The duration of the overall discharge is generally in the range of 200 milliseconds with a time interval of 40 to 60 milliseconds between each of the subsequent discharges. Peak current amplitude as large as 250 kiloamps have been observed during lightning discharges; however, currents of 10 to 20 kiloamps are generally considered to be more typical. Between subsequent discharges, continuing currents of as much as 1000 amps may flow in conductive materials that are interconnected with the facility structure. The rise time associated with a typical lightning flash is in the one to two microsecond range.

Design considerations which attempt to preclude unacceptable interferences to electronic equipments must begin with the recognition that moderately fast rise times and very high current amplitudes are major characteristics of the lightning threat. These characteristics readily cause insulation breakdown, puncture in semiconducting materials, as well as melting of both interconnecting conductors and intra-component elements. The primary mechanisms by which these damages occur are (1) heat deposition resulting from the high current amplitude traveling along resistive and/or reactive conductors and through circuit components, (2) voltage surges magnetically induced into equipments, and (3) voltage surges capacitively induced into equipments. These damage mechanisms may exist individually or in combination.

For the most part, design considerations to preclude lightning stroke damage to equipments must emphasize decoupling of the discharge from the equipments. This situation exists because few if any electronic components can satisfactorily withstand the discharge once it is coupled into the circuitry. The specific design guidelines presented below are directed primarily to achieving this decoupling.

(1) Electrically bond to the lightning down conductor the chassis of any equipment which must be located within approximately 18 inches of a down conductor. This will prevent the short duration but highly damaging flashover that can occur between conducting objects located near lightning down conductors.

(2) Do not route cables terminating in equipments potentially susceptible to voltage surges parallel to conductors that carry lightning discharge currents.

(3) When cables terminating in equipments potentially susceptible to voltage surges must be routed parallel to conductors that carry lightning discharge currents, maintain the separation distance between the cables and conductors as large as possible.

(4) Assure that the loop area formed by cables terminating in equipments potentially susceptible to voltage surges is minimized. When possible, these cables should be twisted together to provide a minimum loop area.

(5) Enclose cables terminating in equipments potentially susceptible to voltage surges in a high permeability shield to reduce the flux density within the loop area formed by the cables.

(6) Assure that voltages which are capacitively induced into equipments as a result of lightning strokes are small by minimizing the total capacitance and effective resistance between the equipment and ground.

(7) To the extent practicable, choose components that are electromechanical in their operation in lieu of solid state and semiconducting components.

(8) Take full advantage of every mechanical design feature of the equipment to provide shielding against inductively and capacitively coupled fields associated with lightning discharges.

VI. NUCLEAR ELECTROMAGNETIC PULSE PHENOMENA

It is a widely recognized fact that nuclear explosions generate a mushroom shaped cloud accompanied by horrendous thermal stresses and radioactive fallout. Less widely recognized is the fact that these explosions also emit extremely high levels of short duration gamma radiation that ultimately generates correspondingly high levels of electric and magnetic fields. Since the originating gamma radiation is short duration, the resulting electric and magnetic fields appear as a pulse of electromagnetic energy. This energy may readily couple into the chasses, circuits, and components of electronic equipment as it propagates through space; therefore, there is a need for design guidelines which will provide at least a degree of protection against the damage that can result from induced electromagnetic pulse (EMP) phenomena.

Design guidelines for protecting electronic equipments against EMP are necessarily concerned with two primary features of the pulse. These features are (1) the exceptionally intense magnetic field component and its coupling characteristics and (2) the overall magnitude of the pulse. In many instances, these two features make design guidelines provided for lightning strokes also applicable for EMP. Specific guidelines are as follows:

(1) In the design and layout of all cabling, interconnecting wiring, etc. provide the minimum practicable loop area in order to minimize magnetically coupled voltages. For example, twist power and signal cables, route wires as close as possible to ground planes, utilize minimum conductor lengths, etc.

(2) Take maximum advantage of every possible feature of equipment design to provide shielding against radiated electromagnetic fields. This applies at the equipment chassis level, at the level of compartments within a chassis, and includes the conductors that interconnect with the equipment.

(3) To the extent possible, shielding materials should have a high permeability and a maximum allowable thickness.

(4) Conductors, wires, cables, etc. that interconnect with electronic equipment should be routed in ferrous conduit, shielded raceway, or cable armor.

(5) At the interconnection between conductor shielding and chassis connectors, electrical continuity should be assured by brazing around the entire periphery.

(6) Carefully consider the relative susceptibilities of different types of components that may be used to accomplish the same design function. For example, electromechanical devices may be as acceptable as semiconductor devices for many switching functions. Concurrently, electromechanical devices will generally offer a significantly enhanced immunity against high level pulse interference.

(7) Jumpers or straps, used either internal or external to the chassis to achieve electrical bonding, should be designed as wide and as short as possible. This will result in a minimum inductance in the jumper or strap and thereby improve the effectiveness with which induced currents are routed to ground.

(8) Design all critical circuits to include transient suppression devices or voltage surge arresters.

(9) Use circuit breakers rather than fuses as protective devices at power input terminals. Circuit breakers can be adjusted to the trip current with a higher degree of accuracy than can fuses and they offer the additional benefit of quick reset. Where fuses must be used, assure that (1) slo-blow or delay types are not used and (2) a periodic schedule of inspection for deterioration is established.

(10) In many instances equipment protection can be realized by deteriorating the abrupt characteristics of the pulse shape. Therefore, conductors used for signal and control purposes should incorporate passive lowpass L-C filters that block high frequency components of pulse-type signals.

(11) The radiated fields from EMP tend to be more intense near discontinuities, corners, and openings in facility materials intended to provide shielding. Consequently, sensitive electronic equipments should be located as far as possible from these areas in the facility.

The above guidelines are basic considerations for incorporation into the design of equipments which might be exposed to EMP fields. However, it should be realized that the intensity of EMP fields is such that protection at only the equipment level is likely to be inadequate. Therefore, equipment designers and facility layout designers need to jointly determine the optimum location, cable routing, etc. for critical equipments.

VII. REFERENCES

1. M. V. Stone, "RFI/EMI Measurements, Air Route Traffic Control Centers", Final Report, Contract No. DOT FA72NA-728, FAA-NAFEC, Atlantic City, NJ, October, 1974.

2. R. F. Ficchi (Editor), Practical Design for Electromagnetic Compatibility, Hayden Book Co., NY, 1971, p. 163.

3. "Interference Reduction Guide for Design Engineers", Vol. II, Contract No. DA36-039-SC-90707, Filtron Co., Inc., New York, NY, 1 August 1974, AD 619 667.

4. See reference 3, Sec. 3-12.

5. See reference 2, p. 154.

6. See reference 3, pp. 3-153 to 3-158.

7. E. E. Von Zastrow, "Coping with RFI and Interaction in Silicon-Controlled-Rectifiers", Electronic Design, Vol. 10, No. 5, 1 March 1962, pp. 54-55.

8. D. R. J. White, A Handbook Series on Electromagnetic Interference and Compatibility, Vol. 3, Don White Consultants, Inc., Germantown, MD, 1973, pp. 17-1 to 17-14.

9. E. R. Hnatek, Design of Solid-State Power Supplies, Chapter 8, Van Nostrand Reinhold Co., NY, 1971.

10. See reference 2, pp. 144-155 and 202-203.

11. J. E. Curran, "Electrical Noise Control", Electro-Tech, Vol. 68, No. 6, December 1961, pp. 117-124.

12. H. N. Dawirs, et al., "Study to Establish Transient Suppression Techniques and Criteria", Phase IV Report, Contract No. NAS8-11362, Recon, Inc., Tallahassee, FL, August 1965.

13. See reference 12, Phase I Report.

14. J. G. Graeme, et al., Operational Amplifiers - Design and Applications, McGraw-Hill Book Co., Inc., New York, NY, 1971.

15. L. P. Hunter, Handbook of Semiconductor Electronics, Section 11 (Low Frequency Amplifiers), Section 12 (High Frequency and Video Amplifiers), and Section 13 (D-C Amplifiers), McGraw-Hill Book Co., NY, 1962.

16. "Instrumentation Grounding and Noise Minimization Handbook", Technical Report AFRPL-TR-65-1, Consolidated Systems Corp., Pomona, CA, January 1965, AD 612 027.

17. H. W. Denny, et al., "Grounding, Bonding and Shielding Practices and Procedures for Electronic Equipment and Facilities", Report No. FAA-RD-75-215, Contract No. DOT FA72WA-2850, Georgia Institute of Technology, Atlanta, GA, June 1975, Vol. 1, Sec. 6.3.1.

18. See reference 17, Vol. 2, Sec. 3.4.2.

19. T. Soller, et al., Cathode Ray Tube Displays, MIT Rad. Lab. Series, Vol. 22, McGraw-Hill Book Co., Inc., New York, NY, 1948.

20. K. James and R. Capodanno, "P-M Focus Devices for Picture Tubes", Electronics, Vol. 24, March 1951, p. 94.

21. "Interference Considerations in Terminal Equipment Design", NAVSHIPS 94328, Contract No. NObsr 72789, BuShips, Electronic Division, Dept. of Navy, January 1961, pp. 41-44, AD 603 866.

22. M. Schwartz, Information Transmission, Modulation and Noise, McGraw-Hill Book Co., Inc., New York, NY, 1959, Chp. 3.

23. "Interference Notebook", RADC-TR-66-1, Contract No. AF 30(602)-3118, Atlantic Research Corp., July 1967, pp. 7-9 to 7-20, AD 484 585.

24. "Design Techniques for Electromagnetic Compatibility", Vol. 2, WBS No. HA010412-F, Contract No. KJ/E/5611/CB17C, Standard Telecommunications Labs, Ltd., March 1969, Sec. 2, AD 857 562.

25. See reference 24, Sec. 4, AD 857 564.

26. See reference 24, Sec. 5.

27. M. I. Skolnik, Introduction to Radar Systems, McGraw-Hill Book Co., Inc., New York, NY, 1962, Chps. 6 and 9.

28. R. W. Landee, D. C. Davis, and A. P. Albrecht, Electronic Designer's Handbook, McGraw-Hill Book Co., Inc., New York, NY, 1957, Section 7.3.

29. See reference 23, Section IV.

30. Part 21 of FCC Rules and Regulations.

31. See reference 28, p. 7-23.

32. See reference 23, p. 4-33.

33. See reference 27, pp. 386-387.

34. See reference 23, p. 4-34.

35. G. A. Rowlandson, "Frequency Synthesis Techniques", Industrial Electronics, August and September, 1968.

36. F. M. Gardner, Phase Lock Techniques, John Wiley and Sons, New York, NY, 1965.

37. See reference 27, p. 409.

38. See reference 28, p. 7-25.

39. See reference 2, Chp. 10.

40. See reference 15, Sec. 15.

41. "Pulsed RF Spectrum Analysis", Application Note 150-2, Hewlett Packard Co., Palo Alto, CA, November 1971.

42. Electromagnetic Compatibility Principles and Practices, NASA Handbook NHB 5320.3, Washington, DC, October 1965, pp. 7-11 to 7-16.

43. See reference 42, Chp. 11.

44. Harlan Stowe, Sr., Stripline Circuit Design, Artech House, Inc., Dedham, MA, 1974, pp. 304 to 306.

45. See reference 24, Vol. 3, p. 3-109.

46. See reference 17, Vol. II, Chp. 3.

47. See reference 3, Vol. 1, AD 619 666.

48. C. B. Pearlston, "Case and Cable Shielding, Bonding and Grounding Considerations in Electromagnetic Interference", IRE Transactions on Radio Frequency Interference, Vol. RFI-4, No. 3, October 1962, pp. 1 to 16.

49. "Interference Control Techniques", Technical Paper 62-1, Sprague Electric Co., North Adams, MA, 1962, pp. 5 and 6.

50. "EMI/RFI Gasket Design Manual", Chomerics, Inc., Woburn, MA, 1975.

51. Electromagnetic Compatibility, AFSC Design Handbook DH 1-4, Air Force Systems Command, 10 January 1972, Design Note 5F6.

52. D. R. Awerkamp, Private Communication, Motorola, Inc., Tempe, AZ.

53. See reference 17, Vol. II, p. 3-33.

54. See reference 17, Vol. I, Sec. 5.5.3.1.

55. See reference 17, Vol. I, Sec. 5.5.3.2.

56. See reference 17, Vol. I, Sec. 4.8.

57. See reference 17, Vol. II, Sec. 1.5.3.

58. H. M. Sachs, et al., "Evaluation of Conductive Glass in Fluorescent Light Shielding Applications", Proceedings of the Sixth Conference on Radio Interference and Electronic Compatibility, October 1960, pp. 281 to 294.

59. See reference 3, pp. 2-176 to 2-182.

60. See reference 3, p. 2-196.

61. See reference 17, Vol. II, Sec. 3.2.

62. See reference 17, Vol. I, Sec. 2.6.